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The systematic development of a machine vision based milking robot

Proefschrift
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in de landbouw- en milieuwetenschappen
op gezag van de rector magnificus,
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in het openbaar te verdedigen
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PROPOSITIONS

1

The significance of technology cannot be asserted in terms of its engineering characteristics alone. Too often, the non-engineering issues, such as socio-economic aspects and ecological aspects, are not thoroughly addressed during technological development - resulting in products which cannot be properly merged with its intended environment.

This dissertation.

2

Since an agricultural environment is in general less structured than an industrial environment, a higher level of robotic performance is required for agricultural automation than for industrial automation. Implementation of industrial robotics will therefore always lead the implementation of agricultural robotics.

This dissertation.

3

A number of practical problems still exist with the implementation of the parabolic Hough transform for localisation of a cow's teats in an edge enhanced image; with three-dimensional scene description based on stereo images; and with the use of two-dimensional camera models for stereo correlation. These techniques have however been demonstrated to possess all the characteristics required by the machine perception subsystem for a milking robot.

This dissertation.

4

The leadership spectrum ranges from *autocracy* to *delegation*. Only the manager who can adapt to different situations, by being able to operate across the whole spectrum - i.e. knowing when to breathe down whose neck and when to leave whom alone - can be assured of continued success.

5

Because of rapid developments in electronics and computer technology, aspects of engineering system design are often neglected in the belief that poor system performance can later easily be corrected by means of monitors and controllers. This represents a fundamentally wrong approach to system design, which all too often leads to very expensive system failures.

6

When teaching system design principles to students, care must be taken not to introduce computer-aided techniques too soon, because it can inhibit the understanding of basic principles, and the development of *engineering judgement* capabilities.

7

In primitive society, communication was mainly by word of mouth; and only the most important information was transferred from one generation to the next. In modern society this inherent filter action has however been lost, because technological developments allow dissemination of information on a very large scale. The result is an *information explosion* (constituting a form of pollution) - which can only be circumvented through increased emphasis on the use of techniques such as artificial intelligence, to filter and control the flow of information.

8

Early populations generally lived in harmony with their natural environments. As soon as their impact on the environment became too harsh, the environment responded by having ill effects upon their health and well-being. In modern society, this natural control system is however increasingly being disturbed, because equal emphasis is not placed on technological developments for enabling man to satisfy needs beyond those associated with survival, and on technological developments for enabling the environment to cope with increased volumes of residues.

9

High atmospheric concentrations of carbon dioxide are a reality of the 1990's - with numerous negative ecological effects. Since the photosynthetic process is a nett consumer of CO_2, large-scale international incentives should be devised to promote the cultivation of "CO_2-hungry" plants.

10

It is better to solve a well defined problem halfway, than to solve a half defined problem in full.

ABSTRACT

GOUWS, J. (1993): *The Systematic Development of a Machine Vision Based Milking Robot*. Ph.D. dissertation, Wageningen Agricultural University, The Netherlands. xvi + 180 pages; 50 figures; 26 tables; 469 references; 5 chapters; 8 appendixes; summaries in English, Dutch, and Afrikaans.

Agriculture involves unique interactions between man, machines, and various elements from nature. Therefore the implementation of advanced technology in agriculture holds different challenges than in other sectors of the economy. This dissertation stems from research into the application of **advanced technology in dairying** - focusing on the **systematic analysis and synthesis of concepts** for a **robotic milking machine** for cows. The main subsystems of the milking robot are identified as a **machine perception** subsystem and a **mechanical manipulator** subsystem. The machine perception subsystem consists of one or more **sensors** and a **signal processor**; while the manipulator subsystem typically consists of a **robot arm**; a **robot hand**; **actuators**; and a **controller**. After the evaluation of different sensor concepts in terms of a defined set of technical performance requirements, **television cameras** are chosen as a suitable sensor concept for a milking robot. Therefore the signal processor is only concerned with **image processing** techniques. The primary task of the milking robot's image processor is to derive a computerized description of the spatial positions of the endpoints of a cow's four teats, in terms of a pre-defined frame of reference (called the *world coordinates*). This process is called *scene description*; and based on extensive experimental results, three-dimensional scene description - making use of a stereo-vision set-up - is shown to be feasible for application as part of a milking robot. Different processes are involved in stereo machine vision - such as data reduction, with the minimum loss of image information (for which the **Sobel edge enhancement operator** is used); the accurate localisation of target objects in the two stereo images (for which the **parabolic Hough transform** is used); and correlation of features in the two stereo images. These aspects are all addressed for the milking robot, by means of concept analysis, trade-offs, and experimental verification. From a trade-off, based on a set of performance requirements for the manipulator subsystem, a **cartesian robot arm** is chosen as a suitable configuration for the milking robot; while sealed **direct current servo motors** are chosen as a suitable actuator concept. A robot arm and its actuators are designed by means of computer-aided design techniques; and computer simulation results are presented for the dynamic response of the arm and its actuators. A suitable robot hand is also designed - based on systematic trade-offs for different parts of a robot hand. From an analysis of the desired controller functions, and of different control concepts, it is concluded that a **positional controller**, making use of **on-line obstruction avoidance**, is required for the milking robot. Because this research project involved **systematic concept exploration**, there are still some details to be sorted out in a follow-up development phase. The basic principles of a **machine vision based milking robot** are however established; and the work in this dissertation represents a suitable baseline for further development.

Key identifiers: *agricultural automation; automated dairying; edge enhancement; image processing; machine vision; milking robot; parabolic Hough transform; robotics; sensor-based robotics; Sobel edge enhancement operator; stereo correlation; stereo machine vision; systematic concept exploration; technical performance requirements; trade-off studies.*

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Gouws, Johan

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'Everyone who is seriously busy with nature and with science, becomes convinced of a Spirit revealing itself in the laws of the universe - a Spirit which is infinitely greater than that of man, and in whose presence we, with our limited powers, should be humble.'

ALBERT EINSTEIN

Although numerous people and institutions have contributed somehow to this research project and the dissertation, I would like to specifically record my sincere thanks and appreciation to the following:

a. My wife Leonie, for her understanding and encouragement during the more than 7 000 hours spent by me on this project, since 1987. Since these hours were spent after normal working hours and over weekends, she had to take over many of my responsibilities. This is very much appreciated !

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I trust that this work will contribute to the process of continually improving the quality of life for people and for animals involved in food production; and that it will stimulate further research on sensor-based robotics in agriculture.

Johan Gouws
Randjesfontein, Midrand, South Africa
May 1992

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EXECUTIVE SUMMARY

The implementation of advanced technology in agriculture, poses different challenges than in other sectors of the economy. Reasons for this include the fact that an agricultural environment is in general less structured than, for example an industrial environment; and because agriculture involves unique interactions between man, machines, and various elements from nature. The specific challenges posed by the application of **advanced technology in dairying** gave rise to this research project.

At the start of this research project, it was concluded that **attaching teatcups to a cow's teats** was the most important activity to be automated before completely automated dairying could become a reality. For this purpose a **milking robot** is required - consisting of a **machine perception subsystem** (one or more sensors and a signal processor), and a **manipulator subsystem** (robot arm, robot hand, actuators, and a controller). There are a number of research institutions where the development of milking robots are in advanced stages already. (An overview of the state-of-the-art is presented in this dissertation.) The reasons why specific system configurations were chosen, are however not always clear from the available literature. Therefore the focus of this research is on the **systematic analysis and synthesis of concepts** for a robotic milking machine for cows.

Before the analysis and synthesis of a milking robot, a number of introductory topics are first addressed in the dissertation. These include: the required level of robotic performance for the implementation of a milking robot; some important changes required to a dairying environment in order to accommodate milking robots; effects of milking robots on milk production levels; effects on animal health; effects on the socio-economic system; and effects on the environment.

Different concepts for the sensors, the signal processor, the robot arm, the robot hand, the actuators, and the controller, are identified, analyzed, and evaluated in the dissertation. In order to evaluate and compare the concepts, a number of technical performance requirements are identified for each segment of the milking robot. Based on the performance parameters, trade-offs are performed, from which the best combination of concepts is chosen. The milking robot configuration suggested in this dissertation is unique in the sense that it is based on a **systematic definition of performance requirements**, a **systematic identification and analysis of concepts**, and **research and development of specific technical issues** regarding the chosen concepts.

In the dissertation, a balance is maintained between reporting on the feasible and the unfeasible concepts. Extensive experimental results obtained with an experimental machine perception subsystem are presented; and a detailed design of, and computer simulation results for the manipulator subsystem are also included.

From a trade-off study, **television cameras** are chosen as the best sensor concept to satisfy the performance requirements defined for a milking robot's main sensor. Because of this sensor choice, the signal processor is only concerned with **machine vision** and with **image processing** techniques. The primary task of the milking robot's image processor is defined as deriving a computerized description of the spatial positions of the endpoints of a cow's four teats, in terms of world coordinates. This process is called *scene description*. It is shown experimentally that two-dimensional scene description, by viewing the udder from below with one camera, is not a feasible concept for the milking robot, since there is too little colour contrast between the teats and the udder of most cows. The teats can therefore not be distinguished from the udder.

Three-dimensional scene description - making use of a stereo-vision set-up - is shown to be feasible; and extensive experimental results are presented. Before a cow's teats can be localised in terms of three-dimensional world coordinates, by means of scene description, they must first be localised accurately in the

stereo images of the udder (i.e. in terms of two-dimensional image coordinates). The first step in this process is to reduce the massive amount of data contained in a grey-scale image, to a more manageable amount of useful information. This can be done by means of **edge enhancement**. For the milking robot, the **Sobel edge enhancement operator** is chosen - based on a qualitative analysis of different operators, and based on the results obtained by other researchers in this regard.

Since the edge enhanced images of cows' teats (viewed from the side) resemble parabolas, the **parabolic Hough transform** is investigated experimentally for localising a cow's teats in terms of image coordinates. This technique is suitable for the detection of multiple parabolas (of any orientation) in an image, and can therefore calculate the image coordinates of a cow's four teat endpoints. The parabolic Hough transform is insensitive for gaps in an edge enhanced image; and good results are obtained - both for the teats in images of an artificial cow's udder, and in images of different real cows' udders.

Stereo correlation (i.e. matching image points in two stereo images) is one of the most difficult tasks in stereo machine vision. For the milking robot, this task is however somewhat simplified, because of the *a priori* knowledge that there are only four teats in each image. A stereo correlation method for objects not necessarily appearing in the same order in the two images, is proposed, and evaluated experimentally in the dissertation. The proposed method (based on two-dimensional camera models) renders good results - provided that no occlusion of teats occur.

A number of practical problems still exist with the implementation of the parabolic Hough transform for localisation of a cow's teats in an edge enhanced image; with three-dimensional scene description based on stereo images; and with the use of two-dimensional camera models for stereo correlation. These techniques are however demonstrated to possess all the characteristics required for successful implementation of a machine perception subsystem for a milking robot.

Although robotic technology is already developed to such an extent that an existing manipulator could possibly be used as part of a milking robot, a custom-made manipulator will much better satisfy the peculiar requirements of a dairying environment. A **cartesian robot arm** (i.e. an arm with independent movement of its endpoint's x-, y-, and z-coordinates), is chosen as a suitable robot arm configuration for the milking robot application; while **direct current servo motors** (provided that they are sealed, to prevent water and dirt from entering) are shown to be a suitable actuator concept. A robot arm and the actuators are designed in one of the appendixes; and its dynamic response is verified by means of computer simulations. The design of a suitable **robot hand** - incorporating two scissor-action fingers - is also presented.

From an analysis of the desired controller functions, of different control concepts, and of the milking robot's environment, it is concluded that a **positional controller**, making use of **on-line obstruction avoidance**, is required for the milking robot.

Because this research project involved **systematic concept exploration**, there are still some details to be sorted out in the next development phase. The basic principles of a machine vision based milking robot are however now well established; and the work in this dissertation represents a suitable baseline, from where further development can commence. In this spirit, suggestions for further work, required in order to implement an advanced development model of the proposed milking robot, are also presented in the dissertation.

A number of aspects addressed in the dissertation are elucidated in the appendixes. The second last appendix contains a list of subjects, and appropriate literature references, related to this research - in order to facilitate future research in related fields; while an extensive list of literature references is included in the last appendix.

SAMENVATTING

In de landbouw geeft de invoering van geavanceerde technologieën andere uitdagingen dan in overige sectoren van onze economie. Reden hiervoor is ondermeer dat een landbouwkundige omgeving in het algemeen minder gestructureerd is dan een industriële omgeving. Bovendien bestaan er in de landbouw unieke interacties tussen mens, machine en verschillende elementen uit de natuurlijke omgeving. De specifieke uitdagingen die samehangen met de toepassing van geavanceerde technieken in de melkveehouderij vormden aanleiding voor dit onderzoek.

Het langs automatische weg aanbrengen van de tepelbekers bij melkkoeien is de nog ontbrekende schakel in de praktische realisatie van de volledig geautomatiseerde melkveehouderij. Daarvoor is een automatisch melksysteem (AMS) nodig. Dit bestaat in de kern uit een perceptiedeel (te weten één of meerdere sensoren en een signaalverwerkingsgedeelte), en een manipulatordeel (robotarm, robothand en -vingers, actuator en een besturingssysteem). Op een aantal (onderzoek)instituten is de ontwikkeling van een AMS in een meer of minder ver gevorderd stadium. In dit proefschrift wordt de huidige stand van zaken weergegeven. Uit de literatuur wordt niet duidelijk waarom voor bepaalde systeem-configuraties wordt gekozen. Daarom ligt in dit onderzoek het zwaartepunt op de systematische analyze en synthese van mogelijke concepten voor een AMS. Daartoe wordt in de inleiding van dit proefschrift eerst kort aandacht besteed aan een aantal relevante aspecten terzake van de noodzakelijke ontwikkelingsgraad van de robotica; wijzigingen in de structuur van de melkveehouderij die nodig zijn voor de implementatie van een AMS; mogelijke effecten op de melkproductie en de dieregezondheid; sociaal-economische aspecten en mogelijke milieu-effecten.

In dit proefschrift worden verschillende uitvoeringsvormen van sensoren, signaalverwerkingssystemen, robotelementen en besturingssystemen nader bekeken. Om de verschillende uitvoeringsvormen te kunnen evalueren wordt eerst voor elk onderscheiden subsysteem een aantal technische eisen gedefinieerd. Tegen de agtergrond daarvan worden dan de verschillende, mogelijke concepten beoordeeld. Tenslotte wordt met behulp van een afwegingsmethode op een systematische wijze de optimale combinatie samengesteld. Op deze wijze ontstaat een ontwerpvoorstel voor een AMS dat uniek is. Immers, er wordt uitgegaan van een volstrekt systematische wijze gedefinieerd programma van eisen, evenzo geïdentificeerde en geanalyseerde concepten en - ten slotte en daarmee samenhangend - het onderzoek en de ontwikkeling van kenmerkende technische elementen.

In dit proefschrift wordt met betrekking tot de rapportage een evenwicht gehandhaafd tussen bruikbare en minder bruikbare concepten. Er wordt een overzicht gegeven van de veelheid van (experimentele) resultaten die verkregen zijn met een experimenteel, gemechaniseerd perceptiesubsysteem. Verder worden een in detail uitgewerkt manipulatorsubsysteem en de computersimulaties hiermee, besproken.

Uit de methodologische ontwerpstudie komt naar voren dat één of meerdere televisiecamera's het beste voldoe(t)n aan de ontwerpeisen zoals die gedefinieerd zijn voor de hoofdsensor van het AMS. Daarom is de signaalverwerking dan ook afgestemd op het toepassen van digitale beeldverwerking. De hoofdtaak van het beeldverwerkingsgedeelte kan worden omschreven als zijnde het vaststellen van ruimtelijke coördinaten, waaruit de positie van de uiteinden van de tepels kan worden berekend. Dit proces wordt "scene description", ofwel beschrijving van de opname-omgeving genoemd. Er kan worden aangetoond dat tweedimensionale "scene description", door met een camera opnamen te maken van de onderkant van de uier, niet voldoet. Er is onvoldoende (kleur) contrast tussen de spenen en de uier, waardoor het onderscheiden vermogen te gering is. Driedimensionale beeldopnametechnieken - waarbij gebruik wordt gemaakt van stereo-opstellingen - zijn wel bruikbaar.

De experimentele resultaten worden op uitgebreide wijze beschreven. Voordat de speenposities kunnen worden vasgelegd in een driedimensionaal coördinatenstelsel, moeten

deze eerst nauwkeurig worden gelokaliseerd in de tweedimensionale stereo-opnamen van de uier, (d.w.z. in de vorm van tweedimensionale beeldcoördinaten). De eerste stap van dit proces bestaat uit het verkleinen van de grote hoeveelheid grijswaarden gegevens tot meer handzame informatie. Dit kan gebeuren door het z.g. opscherpen van de beelden. Voor het AMS wordt gebruik gemaakt van het z.g. Sobel filter. Deze is gekozen op grond van een kwalitatieve analyse van mogelijke operatoren en op grond van bestudering van de onderzoekresultaten van anderen.

Aangezien de aldus verkregen afbeeldingen van de spenen (van opzij gezien) een parabolisch verloop hebben, wordt de Hough transformatie nader onderzocht als middel voor localisering van de speenposities. Deze techniek is geschikt voor het vaststellen van multiple parabole functies (in elke richting) van een afbeelding en derhalve voor het berekenen van de beeldcoördinaten van de uiteinden van de spenen. De Hough transformatie is ongevoelig voor gaten in beelden die opgescherpt zijn. Zowel de experimenten met een kunstuier alsook die met echte uiers gaven goede resultaten.

Stereocorrelatie (d.w.z. de correlatie tussen overeenkomstige punten van stereo-afbeeldingen) is één van de moeilijkste elementen in de driedimensionale beeldverwerking. Bij de ontwikkeling van het AMS ligt dit wat eenvoudiger, er is immers de a priori kennis dat er vier spenen in een afbeelding aanwezig moeten zijn. In dit proefschrift wordt het gebruik van een stereo-correlatiemethode voorgesteld voor objecten die niet noodzakelijkerwijze in dezelfde volgorde op twee afbeeldingen voorkomen. De voorgestelde methode, (die gebaseerd is op tweedimensionale cameramodellen) levert goede resultaten op, mits alle vier spenen op beide beelden zichtbaar zijn.

Er blijven echter nog steeds enkele praktische problemen bestaan zowel bij de implementatie van de Hough transformatie voor het lokaliseren van de speenposities in een opgescherpt beeld, alsook bij driedimensionale beeldbeschrijving, gebaseerd op stereo-opnamen en bij het toepassen van tweedimensionale cameramodellen in stereo-correlatie-technieken.

Er wordt niettemin aangetoond dat al deze technieken de karakteristieke eigenschappen bezitten, die nodig zijn voor een succesvolle implementatie van een machinaal perceptie-subsysteem voor een melkrobot.

Hoewel de robottechnologie zover is ontwikkeld, dat een bestaande manipulator zou kunnen worden gebruikt in een AMS, zal een speciaal aan de in de melkveehouderij heersende omstandigheden aangepaste manipulator, beter voldoen. Een Cartesiaanse robotarm (d.w.z. een arm met onafhankelijke bewegingen van de eindpunten in een x-, y- en z coördinatenstelsel), is gekozen als zijnde een geschikte robotarmconfiguratie in het AMS. Voor de beweging wordt gebruik gemaakt van waterdichte gelijkstroom-servomotoren. Een ontwerp van een dergelijke robotarm wordt besproken in Appendix F. Door middel van simulaties is de dynamische respons onderzocht. Eveneens wordt het ontwerp van een robothand met vingers weergegeven.

Uit de analyze van het programma van eisen van de gewenste regelaar (tegen de achtergrond van de werkomgeving van het AMS) komt naar voren dat een positieregelaar, waarbij gebruik gemaakt wordt van een on-line besturing om obstakels te vermijden, vereist is.

Omdat dit onderzoek zich met name richt op een systematische verkenning van de mogelijke concepten, blijven er nog enige detailaspecten over, die onderdeel moeten zijn van studies in een volgende ontwikkelingsfase. Echter, de basisprincipes van een melkrobot, die gebaseerd is op een beeldverwerkingssysteem, zijn welomschreven. Het werk in deze dissertatie biedt een bruikbare basis van waaruit de verdere ontwikkeling kan beginnen. Tegen deze achtergronden worden aanbevelingen gedaan voor de implementatie van een geavanceerd experimenteel model van een dergelijke melkrobot.

Een aantal aspecten waarnaar in dit proefschrift wordt gerefereerd, wordt in de bijgevoegde appendices nader toegelicht. De voorlaatste bevat een uitgebreide lijst met trefwoorden en onderwerpen die verband houden met dergelijk onderzoek, waardoor toekomstig werk kan worden vergemakkelijkt.

OPSOMMING

Implementering van gevorderde tegnologie in die landbou bied ander uitdagings as in ander sektore van die ekonomie. Redes hiervoor is onder andere die feit dat 'n landbou-omgewing in die algemeen minder gestruktureerd is as byvoorbeeld 'n industriële omgewing; en omdat landbou unieke interaksies tussen die mens, masjiene, en verskeie natuurelemente behels. Die spesifieke uitdagings wat spruit uit die toepassing van **gevorderde tegnologie in melkboerdery**, het aanleiding gegee tot hierdie navorsingsprojek.

Kort na die aanvang van hierdie navorsingsprojek is die **aanhegting van 'n melkmasjien se speenhulse aan 'n koei se spene** geïdentifiseer as die belangrikste aktiwiteit wat geoutomatiseer moet word voordat ten volle geoutomatiseerde melkboerdery 'n realiteit kan word. Vir hierdie doel word 'n **melkoutomaat** (of **robotiese melkmasjien**) benodig - bestaande uit 'n **masjienpersepsie substelsel** (een of meer sensors, en 'n seinverwerker), en 'n **manipuleerder substelsel** (robotarm, robothand, aktueerders, en 'n beheerder). Daar is 'n aantal navorsingsinstellings wat reeds in gevorderde stadiums van melkoutomaat-ontwikkeling is. ('n Oorsig van die huidige stand van die tegnologie word in die proefskrif aangebied.) Die redes waarom bepaalde stelselkonfigurasies gekies is, is egter nie altyd duidelik uit die beskikbare literatuur nie. Daarom is die fokus van hierdie navorsing gerig op die **sistematiese analise en sintese van konsepte** vir 'n melkoutomaat vir koeie.

Voor die analise en sintese van 'n melkoutomaat, word 'n aantal aspekte eers kortliks ter inleiding bespreek in die proefskrif. Dit sluit in: die benodigde *vlak van robotiese ontwikkeling* vir die implementering van 'n melkoutomaat; wysigings benodig in 'n melkery-omgewing ten einde melkoutomate te kan akkomodeer; effekte van melkoutomate op melkproduksie; effekte op dieregesondheid; effekte op die sosio-ekonomiese stelsel; en effekte op die omgewing.

Verskillende konsepte vir die sensors, die seinverwerker, die robotarm, die robothand, die aktueerders, en die beheerder word in die proefskrif geïdentifiseer, en geëvalueer. Ten einde die verskillende konsepte te kan evalueer en te vergelyk, word 'n aantal **tegniese werkverrigtingsparameters** vir elke segment van die melkoutomaat gedefinieer, waarteen die verskillende konsepte gemeet word. Op grond van die werkverrigtingsparameters word daar vir elke segment van die melkoutomaat 'n afspeelstudie gedoen, en word 'n geskikte kombinasie van konsepte gekies. Die melkoutomaat konfigurasie wat in hierdie proefskrif voorgestel word, is uniek in dié sin dat dit gebaseer is op 'n **sistematiese definisie van werkverrigtingsparameters**, 'n **sistematiese identifikasie en analise van konsepte**, en **navorsing en ontwikkeling van spesifieke tegniese aspekte** ten opsigte van die gekose konsepte.

In die proefskrif word 'n balans gehandhaaf tussen dié konsepte wat werkbaar bevind is, en dié wat nie werkbaar bevind is nie. 'n Wye verskeidenheid eksperimentele resultate - soos verkry met behulp van 'n eksperimentele masjienpersepsie substelsel - word aangebied. Verder word 'n gedetaileerde ontwerp, en resultate van rekenaarsimulasies ten opsigte van die manipuleerder-substelsel ook aangebied.

Deur middel van 'n afspeelstudie word daar bevind dat een of meer **televisiekameras** die mees geskikte is om die gedefinieerde werkverrigtingsparameters van die melkoutomaat se hoofsensor te bevredig. Dit impliseer dat **masjienvisie** die aangewese konsep is, en dat **beeldverwerking** die hoofrol speel in die seinverwerker. Die primêre funksie van die melkoutomaat se beeldverwerker is om 'n rekenaar-beskrywing af te lei van die ruimtelike posisies van 'n koei se spene. Dié proses word **toneelbeskrywing** genoem. Daar word eksperimenteel aangetoon dat twee-dimensionele toneelbeskrywing - waar 'n koei se uier en spene van onder af beskou word deur middel van een kamera - nie 'n werkbare konsep vir die melkoutomaat is nie. Die belangrikste rede hiervoor is die gebrekkige kleurkontras tussen die uier en die spene van die meeste koeie - wat veroorsaak dat die spene nie van die uier onderskei kan word nie.

Daar word eksperimenteel aangetoon dat drie-dimensionele toneelbeskrywing - waar 'n koei se uier van die kant af beskou word met twee kameras - 'n werkbare konsep is. Voordat 'n koei se spene egter in terme van drie-dimensionele wêreldkoördinate gelokaliseer kan word deur middel van stereo-visie, moet die spene eers akkuraat gelokaliseer word in die twee beelde (m.a.w. in terme van twee-dimensionele beeldkoördinate). Die eerste stap in hierdie proses is om die groot hoeveelheid data wat in 'n grysvlak-beeld vervat word, te verwerk na 'n makliker hanteerbare hoeveelheid inligting. Dit kan gedoen word deur middel van **randverskerping**. Vir die melkoutomaat word die **Sobel randverskerpingsoperator** gekies - op grond van 'n analise van verskillende operators; en op grond van ander navorsers se resultate.

Aangesien die twee-dimensionele beelde van *koeie se spene (van die kant af gesien)* paraboles is, word die **paraboliese Hough transformasie** eksperimenteel ondersoek vir lokalisering van die speenpunte in terme van beeldkoördinate. Hierdie tegniek is geskik vir deteksie van meervoudige parabole (met enige oriëntasie) in 'n beeld. Die Hough transformasie *is nie sensitief vir gapings in 'n randverskerpte* beeld nie; en goeie eksperimentele resultate word behaal - beide vir lokalisering van spene in randbeelde van 'n kunsuier, en in randbeelde van werklike uiers.

Stereokorrelasie (m.a.w. korrelasie van ooreenstemmende punte in stereo-beelde) is een van die moeilikste take in stereo-masjienvisie. 'n Eenvoudige tegniek vir stereokorrelasie van voorwerpe wat nie noodwendig in dieselfde volgorde in die twee beelde verskyn nie, word in die proefskrif voorgestel en eksperimenteel geverifiëer. Die voorgestelde metode (gebaseer op twee-dimensionele kameramodelle) lewer goeie resultate - mits alvier spene sigbaar is in beide beelde.

'n Aantal praktiese probleme bestaan steeds met die implementering van die paraboliese Hough transformasie vir lokalisering van 'n koei se spene in 'n randverskerpte beeld; met drie-dimensionele toneelbeskrywing gebaseer op stereo beelde; en met die gebruik van twee-dimensionele kameramodelle vir stereo-korrelasie. Daar word egter in die proefskrif aangetoon dat hierdie tegnieke oor al die nodige eienskappe beskik om dit geskik te maak vir gebruik as deel van 'n melkoutomaat.

Alhoewel robottegnologie alreeds in so 'n mate ontwikkel is dat 'n bestaande manipuleerder moontlik gebruik kan word as deel van 'n melkoutomaat, sal 'n doelgemaakte manipuleerder die unieke vereistes van 'n melkery-omgewing baie beter bevredig. As wegspringpunt vir die ontwikkeling van die manipuleerder-substelsel, word 'n **kartesiese robotarm** gekies op grond van 'n afspeelstudie; en **gelykstroom servomotors** word as 'n geskikte aktueerdertipe gekies. (Ten einde te voldoen aan omgewingsvereistes, sal verseëlde motors gebruik word.) Die volledige ontwerp van 'n kartesiese robotarm en sy aktueerders, word in 'n aanhangsel aangebied; en die dinamiese gedrag daarvan word deur middel van *rekenaarsimulasies geverifiëer*. Na 'n analise van verskillende konsepte, word 'n robothand, met twee vingers wat 'n **skêr-beweging** uitvoer, gekies as 'n geskikte konsep vir die melkoutomaat; en die ontwerp van die hand word ook getoon.

Uit 'n analise van die verlangde beheerderfunksies, van verskillende beheerderkonsepte, en van die melkoutomaat se omgewing, word 'n **posisiebeheerder** - wat gebruikmaak van **intydse obstruksie-vermyding** -gekies vir die melkoutomaat.

Aangesien hierdie navorsingsprojek die **sistematiese ontleding van konsepte** behels, is daar steeds detailaspekte wat uitgesorteer sal moet word, in 'n volgende ontwikkelingsfase van die melkoutomaat. Die basiese beginsels van 'n masjienvisie-gebaseerde melkoutomaat is egter behoorlik gevestig; en die werk in hierdie proefskrif verteenwoordig 'n geskikte basislyn vanwaar verdere ontwikkelingswerk kan begin. In hierdie gees word enkele voorstelle vir verdere werk ook in die proefskrif aangebied.

Sommige aspekte wat in die proefskrif aangespreek word, word in die aanhangsels verder toegelig. Die tweede-laaste aanhangsel bevat 'n lys van onderwerpe, en literatuurverwysings, wat verband hou met hierdie navorsing - ten einde toekomstige navorsing in verwante velde te vergemaklik. 'n Uitgebreide lys van literatuurverwysings word in die laaste aanhangsel ingesluit.

CHAPTER 1

GENERAL INTRODUCTION

1.1 BACKGROUND

Implementation of advanced technology in agriculture holds different challenges than implementation of advanced technology in other sectors of the economy. Reasons for this include the fact that an agricultural environment is in general less structured than an industrial environment for example; and because agriculture involves unique interactions between man, machines, and various elements from nature. The specific challenges posed by the application of **advanced technology in dairying** gave rise to this research project. This decision was reinforced by the following:

a. Dairy farming is labour intensive, on a seven-days-per-week basis. In the course of economic development in any country, there is a migration of labour from the primary sectors of the economy (agriculture and mining) to the higher sectors - refer to SINGELMANN (1978) for statistics. The first agricultural operations which are affected by this migration of labour, are the labour intensive ones - such as dairying. The labour needs caused by this migration, can however be overcome through the enhancement and replacement of human workers by technological elements.

b. Besides being sensitive to changes in the labour structure, dairy farming also requires substantial management attention from the farmer/dairy manager. By means of advanced sensor and computer systems, the amount of direct observation and information processing required from the farmer can be reduced - and can also be done at times which are not necessarily dictated by the milking schedule.

c. Two French agricultural economists (BYE & CHANARON (1986)) undertook a study concerning the economic prospects of technology in agriculture. From their study it was concluded that dairy farming was one of the most important areas for future application of advanced technology.

At the start of this research project, it was concluded that **attaching teatcups to a cow's teats** was the most important activity to be automated before completely automated dairying could become a reality. (This aspect is addressed in more detail in Section 2.2.) Therefore the focus of this research falls on the development of **robotic milking machines for cows**.

1.2 GOALS OF THIS RESEARCH

There are a number of groups - mainly in Europe - which are actively busy with research and development on robotic milking machines. (An overview of the state-of-the-art is presented in Section 2.7.) Although some are in advanced stages of development already, the grounds on which specific system configurations were chosen, are not very clear from the available literature (which is rather scarce though). This study therefore aims at the following:

a. To systematically define appropriate **performance parameters** for a robotic milking machine.

b. To systematically identify, analyze, compare, and trade-off different **concepts** for the development of a robotic milking machine's subsystems.

c. To make academic as well as practical contributions in the engineering field of **sensor-based robotics**. This should be done by researching, and solving some of the outstanding technical issues regarding the chosen milking robot configuration.

1.3 PURPOSE AND SCOPE OF THE DISSERTATION

The purpose of this dissertation is to present a discussion and an evaluation of the actions taken in order to satisfy the defined goals of this research project. This dissertation does not only contribute to the better understanding of machine perception, and robotics; but also of some of the implications of merging engineering theory and equipment, with the agricultural sector as the field of application.

During the discussion of the milking robot, concepts which were found not suitable (or perhaps only partially suitable), are also included. This information is considered very important for future research in this field.

Since agricultural engineering uses results from a wide variety of fields, it was impossible to cover all areas to the same depth in the dissertation. It was however an aim to maintain a balance in this regard, and to compile the dissertation such that it can act as a primer for further research in specific areas - in order to fully realize the potential of robotic milking machines.

1.4 COMPILATION AND LAY-OUT OF THE DISSERTATION

Chapter 1 contains a general introduction to the dissertation; the goals of the research; and the purpose, compilation and lay-out of the dissertation.

In Chapter 2 a systematic analysis is performed of the tasks and the associated equipment necessary to automate the milking of a cow. From this analysis, a milking robot and its subsystems are defined. The chapter also addresses the level of robotic performance required for the implementation of a milking robot; some important changes required to a dairying environment in order to accommodate milking robots; some important consequences of milking robots; comments on the life cycle cost of a milking robot; and a summary of the state-of-the-art regarding milking robots.

In Chapter 3, the machine perception subsystem of a milking robot is addressed. For each of its two main segments (**sensors** and **signal processor**) technical performance parameters are defined, and different concepts are identified and analyzed. After different trade-offs it was decided to focus on stereo machine vision as the basis for the milking robot's machine perception subsystem. The chapter contains experimental results obtained from investigating different machine vision concepts.

In Chapter 4, the mechanical manipulator of a milking robot is addressed. For each of its four main segments (**robot arm**, **robot hand**, **actuators**, and **controller**), technical performance parameters are defined, and different concepts are identified and analyzed. From trade-offs it was decided to focus on a cartesian robot arm, with electrical actuators. Although an experimental manipulator subsystem was not constructed as part of this project, detailed designs and computer simulations are presented.

Chapter 5 contains a summary of the results obtained, and the conclusions reached; suggestions for further work regarding the robotic milking of cows; and the overall conclusions.

Appendix A contains details of the experimental machine perception subsystem used for this research project.

Appendix B contains an overview of data reduction techniques suitable for the signal processor of the milking robot's machine perception subsystem. This appendix focuses on techniques for reducing sensor data, while maintaining the information content. For an image processing system, this is done by enhancing the edges in the image, and discarding the rest of the data.

Appendix C describes and illustrates (by means of examples) the Hough transform for detecting and localising curves such as parabolas in edge enhanced images. This technique is used in Chapter 3 for detecting cows' teats in edge enhanced images.

Since this research covers a number of different areas, Appendix D contains a brief "dictionary of terms". Some of the explanations might differ somewhat from those found in the literature or in common use. This is done in order to adapt to the specific context in which the terms are used in the dissertation.

Appendix E contains brief summaries of the different computer programs which were developed and used during this research project. (The program listings - which are obtainable from the author - are not included, since it would make the dissertation too bulky.)

Appendix F contains the *constructional details* of the mechanical design for the manipulator subsystem of the milking robot. (The appendix is thus a close companion of Chapter 4.)

Appendix G contains a bibliography - classified according to subjects relevant for this research project. Under each subject title, only the surnames of the authors and the dates of the relevant publications are given. Full details are contained in Appendix H.

Appendix H contains the complete details of all the references cited (by means of the authors' surnames and the publication dates) in the dissertation and in the bibliography.

1.5 GENERAL CONTEXT OF MILKING ROBOTS

Figure 1.1 summarises the general context of *Milking Robots*. When the diagram is read top-down, it represents the *analytical approach*, by which a system is divided into subsystems, and the subsystems are further divided until manageable entities (such as those shown on the lowest level of the diagram) are reached. When the diagram is read bottom-up, it represents the *systems approach*, by which a system is considered in consecutive higher layers of its intended environment.

For the detailed design of a system, the analytical approach is necessary; but in order to ascertain that the system can be merged with its intended environment, the systems approach is necessary. Since the two approaches are complementary, Chapter 2 addresses aspects of the milking robot in its environment, while the topics on the lowest level in Figure 1.1 are addressed in detail in Chapters 3 and 4.

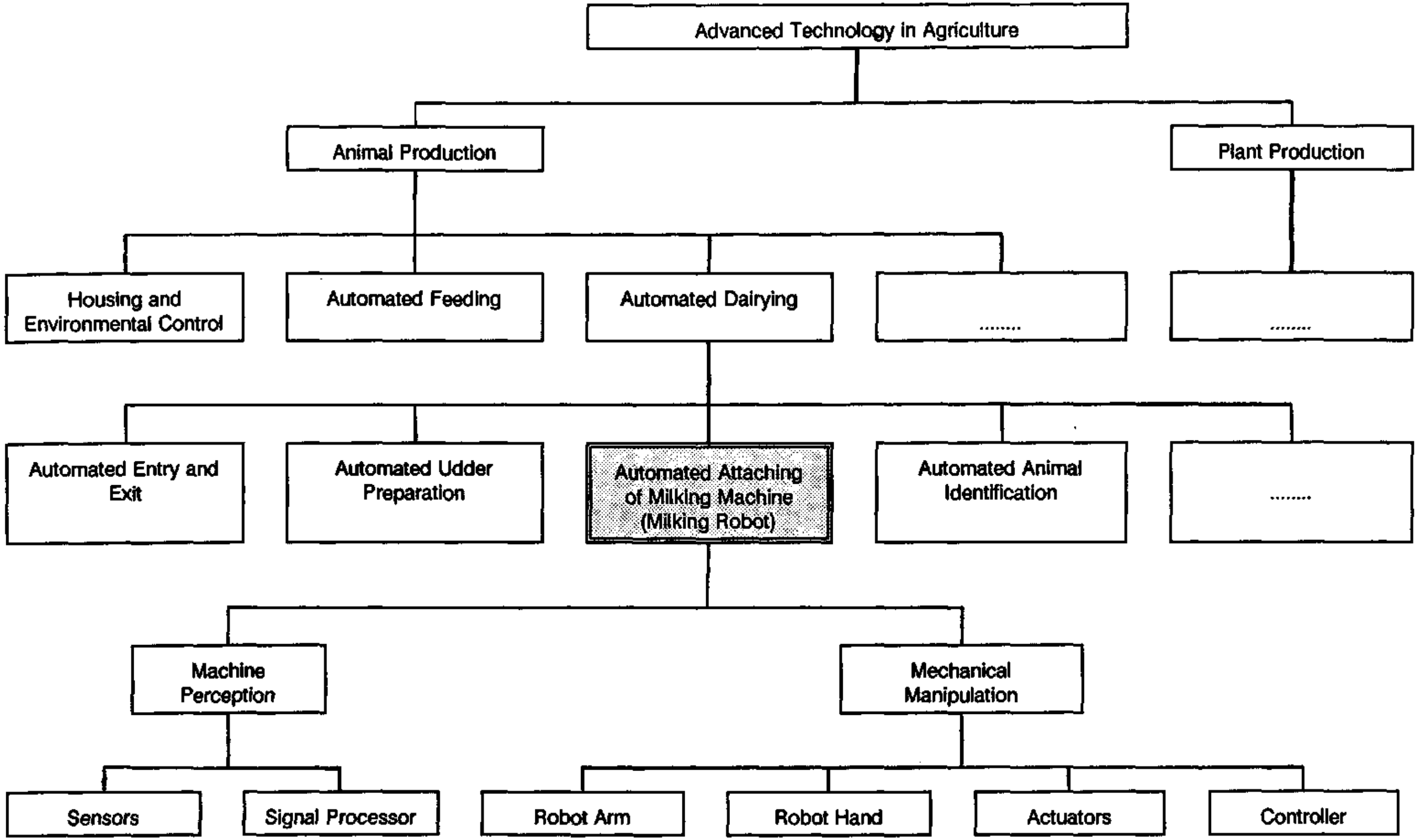


FIGURE 1.1: Schematic representation of a milking robot's environment and its subsystems

CHAPTER 2

ADVANCED TECHNOLOGY IN DAIRYING - FOCUS ON ROBOTIC MILKING MACHINES

2.1 INTRODUCTION

As a first step in the investigation into the use of **advanced technology in dairying**, the actions necessary in order to automate the process of milking a cow are identified. The identified tasks are then matched with available equipment - where possible. A milking robot is then conceptualized in order to perform those tasks for which no existing equipment can be used. From this investigation, the major subsystems for a milking robot are defined.

The *level of robotic performance* required for the implementation of a milking robot is discussed in Section 2.3; while Section 2.4 indicates important changes required to a dairying environment in order to accommodate milking robots.

Some important consequences of milking robots - e.g. potential effects on production levels, on animal health, on the socio-economic system, and on the environment - are presented in Section 2.5; while comments on the life cycle cost of a milking robot are made in Section 2.6.

Before the conclusion of Chapter 2, the state-of-the-art regarding milking robots is summarized in Section 2.7.

2.2 AUTOMATED MILKING OF COWS

The following strategy was followed during this research project for the **identification of needs** in the field of automated milking of cows:

a. Identify and analyze the primary tasks which have to be performed in order to extract milk (other than by a calf) from a cow.

b. Identify existing equipment which can be used to perform the tasks identified.

c. Identify tasks which cannot be performed by existing equipment, and conceptualize appropriate equipment

d. Develop new equipment and systems where necessary, and integrate these with existing equipment, in order to form a system to reduce the direct involvement of humans in the process of milking cows.

2.2.1 IDENTIFICATION OF REQUIRED EQUIPMENT FOR THE REALIZATION OF A ROBOTIC MILKING MACHINE

This section presents details of an investigation which was undertaken at the beginning of the research project, in order to identify tasks and *corresponding equipment for automated milking* of cows. The discussion covers the first three steps of the above strategy, while the fourth step of the strategy is addressed in Chapters 3 and 4 of the dissertation.

(Although the discussion in this section contains well-known information, the intention was to provide a well structured methodology by which dairying tasks could be allocated to different technological elements, in order to automate dairying.)

a. A cow's **entry** into the milking point, can be automated in several ways:
   i. By milking her on every visit to an *automatic feeding station* - *e.g.* as discussed by ROSSING et al (1985).
   ii. By using an automated *selection gate* at a point through which the cows often move, e.g. on their way to drink water - refer to METZ-STEFANOWSKA et al (1989) and KETELAAR-DE LAUWERE (1989).
   iii. By calling a cow to the stall at pre-programmed times, by means of

an electronic signalling device attached to her ear - e.g. WIERENGA & HOPSTER (1987).

b. **Identification** of the cow can be automated by an electronic identification system - of which there are several available commercially. (Refer to *Electronic Identification of Animals* in Appendix G for a list of literature on the subject.)

c. **Stimulation** (for improved letdown of the milk through secretion of the hormone oxytocin - DE VILLIERS (1978)), and **cleaning** of the udder before milking, can be automated by means of rotating brushes and by spraying water onto the udder (e.g. LUSIS & GARANCH (1987) and FARMERS WEEKLY (1990)).

d. It should be possible to use a machine perception system (sensors and a signal processor) for confirmation that a cow's udder is present within the working space (i.e. **recognition**).

e. It should also be possible to use a machine perception system for **localisation** of a cow's four teats, within a pre-defined frame of reference.

f. A machine perception system should also be suitable for **inspection** of a cow's udder and teats, in order to ascertain that they are clean and healthy. (Inspection can either be an integral part of the system's functions, or the system can store information which can later be inspected by a human operator - at a convenient time.)

g. It should be possible to **attach the four teatcups** to the teats by means of a mechanical manipulator - based on the teat positions derived by means of the machine perception system.

h. **Withdrawal of the milk** from the cow's udder is achieved by the pulsating suction of a milking machine - MATON & DAELEMANS (1976), and CASTLE & WATKINS (1979). (The stimulation of the cow's udder at this stage, by applying high frequency vacuum pulses on the teatliners, is also a possibility - e.g. WORSTORFF et al (1987).)

i. **Monitoring and noting of parameters** such as milk yield and udder health can be performed by incorporating various sensors into the teatcup. (Examples of such sensors are discussed by WHEELER & GRAHAM (1986a), ORDOLFF (1987), and TOTH & ESZEKI (1987).)

j. **Removal of the teatcups** from the teats, once the milk flow rate has dropped below a certain threshold can be effected by an automatic vacuum release system, which allows the teatcups to drop off when the milk flow rate drops below a pre-set threshold. (ARTMANN & SCHILLINGMANN (1990) present brief details of some mechanisms to take care of the teatcups once they have dropped off.)

k. **Rinsing and disinfecting** of the teatcups and of the teats can be automated by means of spraying water and a disinfectant onto it after the cow has been milked.

l. A cow's **exit** from the milking point, can be automated by means of an automated gate, and electrically charged chains, lowered onto the cow's back when she must leave. (WIERENGA & HOPSTER (1987) had found in experiments with such a system that cows quickly learned to respond to the noise of the moving chains, without the chains even touching them.)

From the above investigation it became clear that there were two categories of dairying tasks, still requiring further development of appropriate technological elements in order to realize fully automated milking of cows:

a. The recognition, localisation, and inspection of the cow's teats; and

b. Attachment of the milking machine's teatcups to the teats.

It was hypothesized that the technological elements required for these two categories of tasks are a *machine perception system* and a *mechanical manipulator system* - which can be combined to form a *milking robot.*

2.2.2 THE SUBSYSTEMS OF A MILKING ROBOT

A high level and general definition of a **milking robot** is: '*An apparatus to recognize, locate, and inspect the teats of a cow; and to attach a*

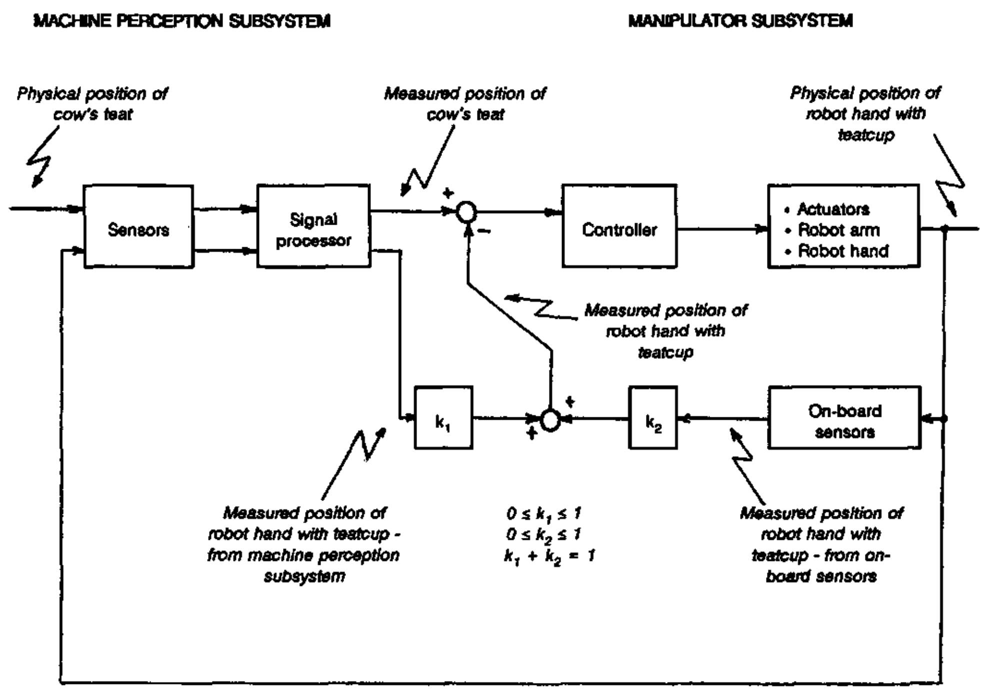


FIGURE 2.1: Generalized blockdiagram representation of a milking robot

milking machine to the cow's teats'. A generalized servomechanism blockdiagram representing a milking robot consisting of a machine perception subsystem and a manipulator subsystem, is shown in Figure 2.1. (The system as shown in Figure 2.1 can be tailored to suit specific requirements - e.g. by choosing different values of k_1 and k_2 within the ranges shown in the figure.)

2.2.2.1 THE MACHINE PERCEPTION SUBSYSTEM

For the milking robot, the machine perception subsystem is defined to consist of one or more *sensors* and a *signal processor*. The sensors, aimed at the cow's teats, provide rough data concerning the teat positions, to the signal processor. This data is processed by the signal processor, such that the teat positions (within certain tolerances) can be derived, and provided to the manipulator's position controller. Different sensors, sensing mechanisms, and signal processing principles for this purpose are discussed in Chapter 3.

(Statistical data obtained from lactation curves, the number of days into the lactation period, and previous teat positions can be used to complement the data derived from the sensors and the signal processor, but it is not considered as a suitable perception technique on its own. More is said about this issue in Section 2.3 below.)

2.2.2.2 THE MANIPULATOR SUBSYSTEM

The manipulator subsystem is used for attaching the teatcups to the cow's teats. This subsystem typically consists of a *controller*, *actuators*, a *robot arm*, and a *robot hand* (or *end effector*). The controller's actions are based on the position reference values generated by the machine perception subsystem; and on position feedback values generated by different sensors - refer to Figure 2.1. The different segments of the manipulator are discussed in more detail in Chapter 4.

2.3 LEVEL OF ROBOTIC PERFORMANCE REQUIRED FOR IMPLEMENTATION OF A MILKING ROBOT

2.3.1 COMMON LIMITATIONS OF ROBOTIC SYSTEMS

The three dimensional localisation of a cow's teats, and the attaching of a milking machine's teatcups to the teats, involve various practical problems, which are only addressed in the design of the most advanced robotic systems. A common practice in the design of industrial robots is to adapt the environment to the robot. This is not always possible in an agricultural environment.

Many industrial robots only make use of two-dimensional observations in specially adapted environments. Consider the sorting of objects for example: The target objects' sizes and shapes are known beforehand, and the objects move at a known speed along a constrained trajectory. The objects can thus be located two-dimensionally by making use of one sensor, while the third dimension of object position is known from the system configuration. (Examples are: manipulation of spare parts on a conveyer belt - ASEA (1983); and candling, sorting and packing of eggs - BOURELY et al (1986).) Similar constraints can obviously not be designed into a robotic milking system's environment.

Another technique often used, is to make use of stored information about target objects. Since the sizes, shapes, and positions of a cow's teats differ for various cows, and even vary from day to day for the same cow, the use of *a priori* information has definite limitations in the milking robot case. Gascoigne-Melotte is one company who implemented this technique in an experimental milking robot. FARMERS WEEKLY (1990) describes a problem experienced during a demonstration of this system: "In one case the different interval between milkings meant that the cow's teats had changed their relative positions. So the memorised co-ordinates were now wrong and a human hand had to help with the final guiding."

Yet another technique which is often used, is to observe a stationary target object two-dimensionally. The manipulator then moves towards the target, until a tactile sensor senses that the manipulator has reached the object - e.g. the automatic fruit picking robots discussed by COPPOCK (1983) and by D'ESNON et al (1986). The construction of a teatcup is necessarily such that the teat must move into it. Tactile sensors can therefore not be used in exactly the same roll as it is used in the case of the fruit picking robot. Furthermore, two-dimensional observation of an object requires contrast between the object and its background. This is a problem when viewing a cow's teats and udder from below - as discussed in more detail in Section 3.4.3.1.

2.3.2 ROBOTIC LEVELS

NEUHEUSER (1989) defines four "levels of robotisation" (based on the robot's level of performance):

a. <u>Preliminary stages of robots</u>, which are remotely controlled operator-driven manipulators. THRING (1983) calls these mechanisms *telechirs*, which literally means *remote hands*.

b. <u>First-generation robots</u>, programmed (or *data-base-driven*) to operate in simplified environmental conditions, and to perform simple repetitive tasks. THRING (1983) calls these machines *senseless robots*, which will try to carry out their tasks, even if the target object is not there, or if something gets in the way. Examples are given by HWANG & SISTLER (1985), and KUTZ et al (1986) (transplanting of seedlings); and GELBGRAS et al (1984) (automated welding and spray painting).

c. <u>Second-generation robots</u>, operating in well structured environments, with the ability to adapt its movements as a result of simple sensory observations. Examples are the manipulation of spare parts on a conveyer belt - ASEA (1983); and the candling, sorting, and packing of eggs - BOURLEY et al (1986).

d. <u>Third-generation robots</u>, operating in natural environmental conditions, making use of **high-performance perception systems**. Examples are given by KEY & ELFORD (1983) (a sheep-shearing robot); and by GERRISH & SURBROOK (1983) and CROWLEY (1985) (mobile robots).

2.3.3 MILKING ROBOT REQUIREMENTS

Telechirs are obviously not suitable for the full automation of dairying, because of the need for an operator. Attempts to derive position reference values for a milking robot purely from stored data regarding a cow's teat positions, represent first-generation robotics; and such systems are not suitable for the full automation of dairying, because of its inability to cope with environmental uncertainties and changes. Second-generation robots are also not suitable for the full automation of dairying either, because of the need for a structured environment, and the limited sensory abilities. Third-generation robots can play a role in the full automation of dairying, because of its adaptability to the environment by means of the machine perception systems used. It should however be clear that these systems make use of advanced equipment, and that they require extensive design effort.

In order to fully utilise the adaptability of third-generation robots, the milking robot concept envisaged for this project is:

a. The machine perception subsystem must be able to localise a cow's teats in real-time. Limited cow movements should thus not prevent the system from operating.

b. The machine perception subsystem must not be disturbed by one or more teatcups already attached to a cow's teats - i.e. once one or more teatcups had been attached, the perception system must still be able to localise the remaining teats in real-time.

c. The manipulator subsystem must be fast enough to attach a teatcup to the teat of a cow - even if she moves around (within certain limits).

d. The teatcups must be held in a retainer rack which can move towards the cow, and from where they can be taken by the manipulator to be attached to the teats. Once milking is completed, the vacuum release system (Section 2.2.1.j) can let the teatcups drop back into the module, and the module can move out of the way again.

2.4 REQUIRED CHANGES TO THE MILKING ROBOT'S ENVIRONMENT

There is a direct relationship between the amount of environmental uncertainties which can be handled by a robotic system, and its "intelligence" and sensing abilities. In designing a robot which can attach teatcups to a cow's teats, both the robot's abilities and the uncertainties in the dairying environment will require intensive design attention, in order to match each other. This section focuses on some aspects of a dairying environment where changes can largely enhance the feasibility of robotic milking.

2.4.1 GENERAL CHANGES REQUIRED

Since the sensor and the manipulator of a milking robot are precision products, care should be taken to limit dirt, dust, and water in the vicinity of these elements. This requires special care with the placement of the sensor and the manipulator, and with the design of the stall's lay-out.

Automated entry of the cows into the stall requires special attention in order to ensure that each cow is regularly milked. (Refer to the discussion in Section 2.2.1.a above.)

A special system for handling the teatcups before its manipulation by the robot, and after milking the cow is required - refer to 2.3.3.d above.

In an automated dairying system, large amounts of information has to be gathered, processed, interpreted, and stored. A master computerised control system, connected to other systems via a communication network, will be required in order to ascertain that there is coordination in the execution of tasks such as automatic feeding; health monitoring; production monitoring; robotic milking; and data logging. (Logging and processing of data is of special importance, in order to ascertain that each cow is regularly milked.)

2.4.2 CONSTRUCTION OF THE STALL

In order to attach a milking machine to a cow by means of a robotic system, the cow's udder must be within a well-defined region of the stall; and the cow must stand as still as possible. (The faster the sensing speed of the perception subsystem and the reaction speed of the manipulator, the less rigid will the requirement be that the cow must stand still.) One or more of the different mechanisms available to centre a cow in the stall and to limit her movements (e.g. moving stall sides - MONTALESCOT &

MECHINEAU (1987); or a floor which is arching upwards between the cow's hind legs, or restraining bars which are moved in between the legs and the udder while the cow stands in the stall - FARMERS WEEKLY (1990)) will thus have to be implemented. A stall with a moving front end (e.g. MONTALESCOT & MECHINEAU (1987)), will also have to be used to provide for cows of various lengths.

2.4.3 CONSTRUCTION OF THE MILKING MACHINE

Some cows have very large udders, with teats far apart and protruding to the sides. In such cases the pipes of the milking machine's cluster (connecting the different teatcups) are often not long enough. When a human milker attaches a milking machine to such a cow, he has to manipulate the teats with his one hand, in order to reach it with the teatcup in his other hand. Since such manipulation is not included as part of the milking robot's functions, this problem must be solved in another way.

A possible solution is to redesign the milking machine in order to have four unconnected teatcups - each with its own vacuum- and milk carrying pipes. Besides the easier robotic manipulation of the teatcups of such a redesigned milking machine, the milking machine could also be adapted to be used as an *individual quarter milking machine* (refer to the definition in Appendix D).

In order to allow for a robotic system's inaccuracies in the positioning of teatcups relative to a cow's teats, teatcups with *wider-than-normal mouths* are used by the company Gascoigne-Melotte. Once the teat has dipped into the teatcup, the brim is inflated by means of air, in order to trap the teat in the centre. This scheme allows for differences of up to 30 mm between the teat and teatcup centreline - FARMERS WEEKLY (1990). Since positional accuracy of a milking robot is an important issue - as discussed in Chapters 3 and 4 - wider teatcup openings definitely enhance the feasibility of robotic milking.

2.4.4 LIMITATIONS ON UDDER SHAPES AND SIZES

Another option to overcome the problem of excessive udder sizes and teats which are far apart and protruding, is to eliminate such cows from the herd, by means of a selection and breeding program. Good results obtained with *selection and breeding for easier robotic milking*, were reported by POLITIEK (1987).

2.5 CONSEQUENCES OF ROBOTIC MILKING MACHINES

2.5.1 INFLUENCE ON MILK PRODUCTION LEVELS

When milking with a robotic milker, it will be possible to milk all the cows in the herd more than the conventional twice per day. ROSSING et al (1985) and IPEMA et al (1987) conceptualized the installation of a milking robot in an automatic feeding station. In order to investigate the feasibility of this concept, a milking machine was installed next to a feeding box, and operated manually on a 24 hour per day basis. The following results were recorded:

a. Cows visited the feeding station voluntary on average 3,9 times per day, and could be milked on every visit.

b. The higher milking rate resulted in an average increase in milk production of 14%, over the full lactation period (compared with the control group).

c. A mass increase in the order of 10% occurred in milkfat and protein production, over the full lactation period (compared with the control group).

d. No negative effects on reproduction performance of the cows, or on teat and udder health, were recorded.

e. No negative effects were recorded regarding milk quality.

GRIMM & RABOLD (1987) recorded milk production increases of up to 20% when cows were milked four or more times per day. The use of milking robots make this milking frequency possible.

From the abovementioned results obtained by other researchers, it is evident that the use of milking robots can result in significant increases in milk production levels. Increased total production is however not necessarily desirable - due to over-production and quotas in many countries. If the same milk production volumes can however be reached with less animals, the advantages are obvious.

2.5.2 INFLUENCE ON ANIMAL HEALTH

When advanced technology such as milking robots, is implemented as part of an animal production system, one of the most important questions is concerned with its influence on animal health. Since little direct feedback can be obtained from the animals, regarding a specific system's influence on them, the designer must take full responsibility for this aspect. The analysis of the man-machine interface is a very important part in the design of systems to be used by human operators (e.g. KEIRN & AUNON (1990); SHERIDAN & FERRELL (1974); SINGLETON (1978); and WICKENS et al (1989)). In similar fashion, machine-animal interface aspects should be rated very important in the value system when systems are conceptualized and designed for the automation of animal production.

Remote sensing and automatic animal identification form the basis for a robotic milking system. This requires an electronic receiver/transmitter ("transponder") to be attached to the animal. Although the electromagnetic radiation associated with such devices apparently have no negative effects on animals, differences of opinion still exist as to the long-term effects of such devices on body tissue. Only an in-depth investigation - which is beyond the scope of this research however - can answer this question.

Attaching transponders to animals is done in various ways - e.g. implanted capsules, or as an eartag, or on a strap around the animal's neck, or on a strap around its body. It is sometimes noted that animals continuously move their ears, because the eartags hinder them. In other cases the transponder's neck band hurts the animal's neck. Since automatic animal identification is essential for robotic milking, the above aspects represent indirect negative consequences of milking robots - which must be prevented.

Stress is an important aspect influencing a dairy cow's production, and her health. GIESECKE (1983, p.23) correlates cow stress and the occurrence of mastitis: "The stress exposure of cow and udder [...] eventually terminate in mastitis [...]". In many cases, the close interaction with human milkers cause stress for dairy cows. SEABROOK (1972) carried out some work in which it was shown that a cow's stress level and milk yield are related to the cowman's personality. Specifically, an introvert personality appears more suitable for successful milking and herd husbandry. With automated dairying, the amount of interaction between the cows and the cowman is reduced, which will lead to less human induced animal stress; and thus to increased milk production, and to improved animal and udder health. On the other side of the coin however, is the possible increased stress levels due to a cow's interaction with machines such as a feeding station, a milking machine, and a milking robot. From available literature it seems that this aspect has not yet received much research attention. It will definitely have to be addressed in future research - possibly along the lines of the man-machine interface studies mentioned above.

Although less interaction between a cowman and his animals can lead to decreased stress levels for the animals, it also results in decreased human monitoring of the animals, which can have negative effects on animal health. However, the data gathered by means of different sensors can be processed faster, and more consistently by means of the automated system's computer. Furthermore, the sensors and processors of an automated system should be available continuously - which is not the case with human monitoring of the animals.

Mastitis control is probably one of the most important tasks in modern dairying. With more regular milking of the cows, and with automatic mastitis detection, udder health can be well monitored in a robotic milking system. A major cause of mastitis is an udder not being milked out completely, and the subsequent long time before the next milking. With more regular milking, this problem should be reduced.

Increased production levels cause larger and heavier udders. This can in turn cause hip and leg problems with some cows - due to the heavy loads which have to be carried for the long periods between milkings. With the more regular milking which is possible when using milking robots, the problem of heavy udders can be considerably reduced.

From the above discussion, it can be concluded that the use of advanced technological elements in animal production systems can have both negative and positive effects on animal health. The potential negative effects can however be avoided by the designer through adequate design techniques, and by the farmer through adequate management practices; while the positive effects can be very advantageous to both the farmer and his animals. MONCASTER & PARSON (1987) summarise it as follows: "Since there is more time for cowmen to attend to the cows, greater opportunity to monitor their performance and state of health automatically, and also the possibility of tailoring the milking process to suit the needs of individual animals, welfare of the cows could be improved."

2.5.3 SOCIO-ECONOMIC EFFECTS

The significance of automation cannot be asserted in terms of its engineering characteristics alone. Therefore some of the socio-economic effects of robotic milking machines are briefly discussed in this section.

An often heard argument against the implementation of agricultural robotics is the possible negative influence on the number of jobs available. As far back as 1968, IRVING's research had however indicated that appropriately managed automation increase the gross domestic product of a country. That in turn contributes to the creation of more jobs, and to economic growth. KRUTZ (1983) quotes figures from the (American) Society of Manufacturing Engineers (SME), forecasting that about twenty thousand Americans could lose their jobs in the 1980's due to robots. On the other hand, an estimated seventy- to one hundred thousand new job opportunities could be created by the robotics industry at the same time.

An important aspect in the use of advanced technology in agriculture, is the improvement of working conditions for farm workers. NITZAN (1985) considers avoidance of tasks which are undesirable for humans as the most important driver for automation. In the dairying context, the use of milking robots can relieve people from monotonous tasks (e.g. repetitive attaching of milking machines to cows), continuous hard work (e.g. seven days per week, all-year round milking of cows), and dangerous work (e.g. handling bad tempered cows).

FALKENA (1979) considered the consistent use of technology as one of the main factors making high levels of agricultural productivity (ratio of yield to input costs) possible - with a significant influence on the macro-economy. Productivity is often linked only with the skills, attitudes, and knowledge of workers. Although people play a central role, all the production factors (natural resources, human resources, money, entrepreneurship, and **technology**) must be used well, in order to optimize productivity.

2.5.4 ENVIRONMENTAL EFFECTS

In the Netherlands for example, disposal of animal waste is a major problem, having a large impact on the environment. If the required milk production volumes can be reached with less animals, less animal waste will be produced; and the use of milking robots will thus have an indirect positive influence on the environment.

2.6 COMMENTS ON LIFE CYCLE COST AND ECONOMIC IMPLICATIONS OF MILKING ROBOTS

From a commercial viewpoint, and in order to ascertain the feasibility of milking robots, it is important to compare its life cycle cost with that of conventional milking machines. However, a pure cost comparison will not provide the full picture, for the following reasons:

a. There are differences in the functions and in the technological complexity of the two systems. The two systems are therefore *appropriate for differently developed societies*.

b. There are differences in the direct and indirect costs and savings for the two systems. (Refer to POTTER (1983) for the importance of this issue when deciding to automate a process or not.)

In order to restrict the scope of the research, and to maintain focus on the **exploration of technical concepts**, it was decided not to perform extensive investigations into a milking robot's life cycle cost, or its economic implications - such as that presented by ECKL (1988), NIJSSEN *et al* (1988), and MONCASTER & PARSON (1987). Suffice it to quote the following conclusion reached by the latter: "For herd sizes of 40 cows or more, the numbers of automatic milking units required are between a quarter to half of the number of stalls required in a conventional milking system. Thus, although the fully automatic system requires components which are more expensive to buy, run and maintain than those of conventional milking systems, the total costs for a given herd size are not markedly different."

2.7 OVERVIEW OF THE STATE-OF-THE-ART IN MILKING ROBOTS

In this section, an overview is given of the state-of-the-art regarding milking robots - based on a literature survey. There are a number of research institutions and companies (from the available literature, they seem to be mainly in Europe) which are actively involved in the development of different milking robot concepts. Because of the commercial value of such developments, most of this work is however not yet made public; and therefore the literature on the subject is rather scarce.

By making use of information presented by ARTMANN & SCHILLINGMANN (1990); ORDOLFF (1983); KLOMP et al (1990); MARCHANT et al (1987); ROSSING (1988, 1989); and SWORMINK (1991), the summary in Table 2.1 could be compiled. From the available literature it seems that the milking robot developments in the Netherlands are currently the most advanced. Although SWORMINK (1991) states that *"it will still be some years before milking robots can be bought from the local corner shop"*, several developers are confident that they are on the right track with their work.

TABLE 2.1: Summary of the state-of-the-art regarding milking robots

DEVELOPMENT CENTRE	SENSOR CONCEPT	ROBOT ARM CONCEPT
AFRC, Silsoe, United Kingdom	CONCEPT 1: (according to ROSSING (1989)) - Two ultrasonic sensors for localisation of teats (accuracy about 60 mm) - Cone shaped teatcups, with tactile sensors CONCEPT 2: (according to ARTMANN & SCHILLINGMANN (1990)) - Tactile sensors for coarse localisation of the cow; and data base of teat positions - Array of light beams for fine localisation of teats	- Pneumatically actuated robot arm, with two rotating wrists and one linearly moving axis (spherical arm) - with an accuracy in the order of 5 mm - All four teatcups taken simultaneously to the udder
Bundesforschungsanstalt für Landwirtschaft, Braunschweig-Völkenrode, Germany	CONCEPT 1: - Array of ultrasonic sensors for coarse localisation of teats - Two ultrasonic sensors for fine localisation of teats CONCEPT 2: Laser diode and one television camera for localisation of teats (mounted on robot arm)	- Electrically actuated robot arm, with four degrees of freedom: three linearly moving axes (cartesian arm), which can also rotate about its vertical axis - Teatcups consecutively taken to the udder

DEVELOPMENT CENTRE	SENSOR CONCEPT	ROBOT ARM CONCEPT
CEMAGREF, Antony, France	- Scanned laser diode and one television camera for coarse localisation of teats - Array of light beams on the teatcup, for fine localisation of teats	- Separate robot arm for each teatcup - Electrically actuated robot arms
Dűvelsdorf, Otterberg, Germany	- Data base of teat positions, for approximate localisation of teats - One scanned ultrasonic sensor for coarse localisation of teats - Array of light beams for fine localisation of teats	- Electrically actuated robot arm, with three linearly moving axes (cartesian arm) - Adapted industrial robot arm - Teatcups consecutively taken to the udder
Gascoigne-Melotte, The Netherlands	- Positioning of the cow in the stall, by means of moving stall sides and -front - Data base of teat positions, and wider-than-normal teatcup openings	- Electrically actuated robot arm, with two linearly moving axes, and one rotating wrist (cylindrical arm) - All four teatcups taken simultaneously to the udder (in a *module*) - Teatcup positions in the horizontal plane are individually controllable in the module - Teatcups approach the udder from behind, and move in between the hind legs
Prolion, The Netherlands; *inter alia* in co-operation with: - IMAG, Wageningen, The Netherlands - Manus Holland, Zutphen, The Netherlands - Delft University of Technology, The Netherlands	- Two ultrasonic sensors for coarse localisation of teats - One rotating ultrasonic sensor for fine localisation of teats	- Electrically actuated robot arm, with three rotating wrists (articulated arm) - All four teatcups taken simultaneously to the udder - Teatcups attached from the side of the cow

From the information in Table 2.1 it is clear that there are at least as many milking robot concepts as there are developers. From the literature, it is however not clear what the exact requirements are which each developer has used as the driver in order to choose his specific concept. Nor is it always clear why one concept was preferred over another. Therefore the goals of this research project - as identified in Chapter 1 - are centred around the systematic **definition of performance parameters** for a robotic milking machine; the systematic **identification, analysis, comparison, and trade-off of different concepts** for a robotic milking machine's subsystems; and **research and development of chosen concepts**.

2.8 CONCLUSIONS

From an investigation of the tasks performed by a human, when milking a cow, the technological developments required in order to automate this process were identified. From this investigation it was concluded that the main outstanding activity in order to completely automate the milking of cows, is the development of a milking robot - consisting of a machine perception subsystem for localising the teats, and a manipulator subsystem for attaching the milking machine to the teats.

From the discussion in Section 2.3 on the level of robotic performance required for the implementation of a milking robot, it was concluded that a *third-generation robot* - making use of a high-performance perception system in order to adapt to the environment - is required for locating a cow's teats, and for attaching teatcups to them. Such robots however make use of advanced equipment, and they require extensive design effort - as will become evident in the next two chapters.

A number of changes to a dairying environment, which will greatly enhance the feasibility of robotic milking, were addressed in Section 2.4. General aspects addressed included the placing of the sensor and the manipulator; automated entry of the cows into the stall; handling the teatcups before the robot attaches it, and after milking; restriction of the cow's movements; and the need for an extensive information management system, to coordinate the execution of different automated dairying tasks. Changes to the construction of a milking machine - such as a milking machine with longer-than-normal pipes attached to the teatcups; and teatcups with wider-than-normal mouths - will also enhance the feasibility of robotic milking. The issue of selecting and breeding cows for easier robotic milking, was also briefly addressed in Section 2.4.

Some important potential consequences of milking robots - including effects on production levels; effects on animal health; effects on the socio-economic system; and effects on the environment - were presented in Section 2.5. Different researchers recorded increased milk production levels when milking cows more than the conventional twice per day. Since a robotic milker can increase the milking frequency, it can lead to better productivity (e.g. the same production from less cows); less animal waste to be handled; and to lighter loads in the cows' udders. Automated milking leads to less interaction between a cowman and his animals. This can lead to decreased stress levels for the animals, but it also results in a decreased human monitoring of the animals. The automated system is however part of a computerized information management system, by which the data gathered by means of different sensors can be processed faster, more consistently, and probably continuously. An important social advantage of robotic milking is the improvement of working conditions for farm workers; while increased agricultural productivity has economic advantages over a wide front.

In order to focus on the exploration of technical concepts, it was decided not to perform extensive investigations into a milking robot's life cycle cost, or its economic implications. Section 2.6 was therefore restricted to some reasons why milking robots and conventional milking machines should not be compared one-to-one on economic grounds; and to providing some literature references containing detailed studies of the economic implications of robotic milking.

Based on a literature-survey on the state-of-the-art regarding milking robots, it seems that there are at least six main centres in Europe where specific milking robot configurations are at different stages of research and development. (For each of these there is a main developer, in collaboration with different universities, research institutions, and companies.) Since it was not clear from the available literature which decision-criteria and concepts were considered by the different developers, it was decided to systematically address these issues in this research project. The milking robot configuration presented in this dissertation is therefore unique in the sense that it is based on a systematic definition of performance requirements, a systematic identification, analysis, and trade-off of concepts, and research and development regarding the chosen concepts. The details of this process are presented in the following chapters.

CHAPTER 3

MACHINE PERCEPTION FOR A ROBOTIC MILKING MACHINE

3.1 INTRODUCTION

3.1.1 BACKGROUND ON MACHINE PERCEPTION

Machine perception can broadly be defined as *the process whereby a computer derives information about a scene, based on signals from one or more sensors.* The primary function of a milking robot's machine perception subsystem is to determine a cow's teat positions, in real-time, with respect to a fixed frame of reference. Recognition (in the sense of distinguishing different objects in the scene) and inspection of the cow's teats are secondary functions of the machine perception subsystem.

Machine (or computer) perception consists of two main processes, namely:

a. Feature transformation, which involves the conversion of physical features in a scene or an environment (such as light intensity, temperature, force, etc.) to electrical signals, by means of sensors.

b. Signal processing, for data reduction, data analysis (e.g. object localisation in terms of the sensor's frame of reference - so-called *sensor coordinates*), and scene/environment description (e.g. object localisation in terms of a specifically defined fixed frame of reference - so-called *world coordinates*).

The effective design of a machine perception system is based on the optimal implementation of the abovementioned two processes. (Refer to SANDERSON & PERRY (1983, p.858), and to NITZAN (1985, p.6) for more detailed discussions of these processes.) The implementation of these processes for a specific application, does not only involve the correct choice of sensors and of signal processing techniques, but also requires a well structured information interpretation system.

3.1.2 PURPOSE AND SCOPE OF CHAPTER

Different concepts for the sensors, and the signal processor of the machine perception subsystem for a milking robot, are identified, analyzed, and evaluated in this chapter. In order to evaluate and compare the concepts, a number of technical performance requirements are identified for each of the segments; while each concept is then evaluated against its requirements. From this evaluation, a combination of concepts is chosen, in order to design a suitable machine perception subsystem for a robotic milking machine.

In the presentation of research results, a balance should be maintained between reporting on aspects and schemes which did not work, and reporting on those which did work. (This approach provides important guidelines for future researchers in the same field.) This chapter therefore contains analytical discussions of numerous machine perception concepts. Explanations are presented regarding those concepts which were found unfeasible for the milking robot; while experimental results obtained with the feasible concepts, are presented.

3.2 ANALYSIS OF THE MAIN SENSOR FOR A MILKING ROBOT

3.2.1 TECHNICAL PERFORMANCE REQUIREMENTS FOR THE SENSOR

In this section a number of **technical performance requirements** which must be satisfied by the sensor of a milking robot, are defined and compared with each other in order to determine their relative importance. The parameters defined are necessarily based on the author's own experience in the fields of system design and dairying. The defined parameters are the most important ones, and are not intended to be the alpha and the omega of milking robot requirements. Also note that life cycle cost and acquisition schedule are not included in this discussion, since the focus is on the *exploration of technical ability*.

The sensor cannot meet the requirements listed in this section, on its own, but it depends on the signal processor to do so. However, the sensor's sensitivity and resolution, as well as the type and amount of information that can be gathered by it, play a very important role in the machine perception process.

The different requirements against which the sensor concepts are evaluated, influence each other. Although the requirements can thus not be considered in isolation, the aim is to decouple them as far as possible, and to analyze the sensor concepts against one requirement at a time.

3.2.1.1 DEFINITION OF PERFORMANCE REQUIREMENTS

The most important technical performance requirements which must be satisfied by the sensor of a milking robot, are:

a. Recognition of objects. The first tasks performed by a human milker when a cow enters the stall to be milked, is to confirm that the udder is present within the working space; and to distinguish the udder and teats from other objects - such as pipes - within the working space. With a human milker, *detection* and *distinction* take place automatically, but these functions (collectively called *recognition* here), must be designed into a milking robot's machine perception system. (The main reason for considering this aspect to be very important, is for the milking robot to distinguish between teats and milking machine pipes and teatcups, once one or more teatcups had been attached.)

b. Localisation of objects. The main purpose of the machine perception subsystem of a milking robot is the accurate *localisation* of the cow's teats, in order to provide position reference values for the manipulator subsystem of the milking robot. (As indicated in Figure 2.1, the machine perception subsystem could possibly also be used to help with localisation of the robot hand. This option will however not be investigated during this research.)

c. Inspection of objects. An important human function to be taken over by the milking robot, is *inspection* of the udder and teats, in order to ascertain that they are without ulcers or cuts on the teat surface. This can either be an integral part of the system's functions, or the system can store information which can later be inspected by a human operator - at a convenient time. (Inspection of the milking machine and the manipulator can also be included.)

d. Sensor simplicity. In order to ascertain simple operation, low cost, high reliability, and easy maintenance of the machine perception subsystem, the sensor's operating principle must be as simple as possible. Furthermore, the data generated by the sensor should not require a very complex signal processor.

e. Environmental compatibility. The milking environment (especially when milking in a feeding box - as discussed in Chapter 2) can be adverse. For this reason the sensor must be water-, dust-, dirt-, and shock resistant; or it must be mounted such as to ascertain these traits.

f. Sensing speed. The machine perception subsystem must perform real-time observations in order to enable the system to attach the milking machine to the teats. Therefore the sensor must have the ability to transform scene features to electrical signals in real-time. The complexity of the data generated by the sensor, and of the signal processing required, also determine sensing speed.

g. Interfacing. In order to minimize cost and overall system complexity, the sensor's interfacing with the signal processor and data storage units must be as simple as possible.

3.2.1.2 WEIGHTING OF PERFORMANCE REQUIREMENTS

In Table 3.1 the different technical performance parameters for the sensors (as defined in Section 3.2.1.1) are compared with each other, in order to determine their relative importance - indicated by the *weight* factor. (Remember that life cycle cost and development schedule are not used as performance parameters here, since the focus is on the technical appropriateness of the different concepts.) In

Table 3.1, 21 pairs of performance parameters are compared with each other. For each pair of parameters, a total rating of 10 is allocated. That allows for six levels of relative importance (10+0; 9+1; 8+2; 7+3; 6+4; 5+5). If parameter A is considered just as important as parameter B, then each is allocated 5. If A is slightly more important than B, then A is allocated 6, while B gets 4; etc.

The comparison is done cell by cell in each column (staying below the diagonal). In each cell, the parameter listed at the top of the column is compared with the parameter listed left of the specific row. (For example, in the *second column (first numerical column)* of Table 3.1, *Recognition of Objects* is compared with the other six defined performance parameters; while in the third column, *Localisation of Objects* is compared with the last five parameters; etc.) Depending on the perceived importance of the parameter listed at the top of the column, relative to the one listed left of the specific row, a number between 0 and 10 is allocated in the specific cell. The mirror images of the cells (i.e. above the diagonal) get the 10's complement of the numbers allocated below the diagonal. After all the pairs have been compared and rated (and the mirror images allocated the 10's complements), the ratings within each column are added to provide the total rating for each of the parameters listed at the top of the columns. These ratings are then *rounded, and expressed as percentages* (called the *weight*).

	Recognition	Localisation	Inspection	Sensor simplicity	Environmental compatibility	Sensing speed	Interfacing
Recognition	-	6	6	3	5	6	2
Localisation	4	-	2	2	4	3	1
Inspection	4	8	-	4	7	5	2
Sensor simplicity	7	8	6	-	8	6	5
Environmental compatibility	5	6	3	2	-	4	1
Sensing speed	4	7	5	4	6	-	1
Interfacing	8	9	8	5	9	9	-
Sum of components	32	44	30	20	39	33	12
Weight (%)	15	21	14	9	19	16	6

TABLE 3.1: Determination of relative weights for sensor trade-off parameters

3.2.2 IDENTIFICATION OF SENSOR CONCEPTS

There is a large number of sensor concepts which are commonly used in the field of robotic control. (Refer to SANDERSON & PERRY (1983) for a broad discussion of this topic.) The primary function of the main sensor (or sensors) in the *machine perception subsystem* of a milking robot, is to provide information about the scene containing the cow's udder, to the signal processor, in order that the cow's teat positions can be determined. This section contains discussions of sensors which can possibly fulfil this task.

3.2.2.1 TELEVISION CAMERA

In the human sensory system, two thirds of the roughly three million information carrying fibres *connected to the brain, come from the eyes* - YOUNG (1973, p.23) and WOOLDRIDGE (1963, p.34). It is therefore clear that the eyes are the most important human sensing organs. With two eyes (or one moving eye), three-dimensional object localisation is possible. Of all the human senses, vision proves the best for perceiving the presence of objects, for object recognition, and for inspection (typically through image features such as shape and texture). For these reasons, a television camera (as part of a machine vision system) is very popular for machine perception applications.

3.2.2.2 ARRAY OF LIGHT BEAMS

One or more light rays aligned with light detectors can be used to detect the presence or absence of objects within a certain space. ORDOLFF (1983) describes the use of such a system in order to detect the presence of a cow in the stall, and to find the front of her udder.

This technique is rather simple to implement, but its scope in machine perception applications is limited, because it merely detects the presence or absence of objects. It does not have the ability to derive extensive information about the scene (e.g. for inspection purposes).

An extension of the technique is the use of structured light, which is commonly used to augment machine vision. By illuminating a scene with a single light stripe or with patterns of orthogonal light stripes, and by studying the resulting light patterns in an image of the scene, a lot of scene information can be derived. Various discussions of this technique are presented in the literature - e.g. LE MOIGNE & WAXMAN (1988); MITICHE & AGGARWAL (1983); SATO et al (1982); SHIRAI (1972); SHIRAI & TSUJI (1972); and STOCKMAN et al (1988).

3.2.2.3 ULTRASONIC SENSOR

Ultrasonic sensors are widely used for ranging applications - making it suitable for localisation of objects. While it can also be used for low-level recognition of objects, it is not suitable for the detail characterisation of image features (inspection of objects). A problem with ultrasonic sensors is the scattering of ultrasonic energy away from the receiver, when the object plane is not perpendicular to the acoustic beam - refer to BROWN (1985, p.191), JARVIS (1983, p.135), and GREENLEAF (1983).

Based on extensive research, ACAMPORA & WINTERS (1989) concluded "[...] that the approach [of ultrasonic sensing] offers promise as a complement to or replacement for a conventional optical system [...]." From their research it is evident however that ultrasonic machine perception systems are not yet on the same level of development as optical systems.

3.2.2.4 TACTILE SENSOR

Tactile sensors are mainly used to detect the presence of objects by touching them; or to measure distributions of forces over a surface. It is commonly used in feedback loops for the control of robot hands - e.g. D'ESNON et al (1986), HARMON (1982), JACOBSEN et al (1988), and TZAFESTAS (1988). Very little scene features can however be detected by this type of sensor.

3.2.2.5 INFRARED SENSOR

An infrared sensor forms an image of a scene, based on the amount of infrared light (heat) emitted by each object in the scene. Only limited image features (for inspection of objects) can be detected by this type of sensor.

Infrared sensors are often used in military applications, where the target is normally the only large heat source in the area. For example, the infrared image produced by the exhaust plume of a fighter aircraft is unique, when viewed against a clear sky as background. For military applications, the required localisation accuracy is typically in the order of a few metres.

For a milking robot, high accuracy is required; and the targets (four teats) are close together, and in the vicinity of other heat sources (e.g. the cow's body and udder). ORDOLFF (1983) found that absolute temperature could not be used for detection of a cow's teats by means of infrared imaging, since temperatures differed to a large extent from one cow to another. Neither could temperature differences (between teats and udder, and between udder and body) be used, because it was impossible to find typical differences.

3.2.2.6 MINIATURE RADAR AND LIDAR

Miniature radar, and lidar (the light equivalent of radar) are often used for ranging applications - e.g. in military systems. (Laser beams are often used for lidar ranging. Lasers normally have very high energy densities, which might be dangerous for humans and animals - especially for the eyes. Therefore so-called eye-safe lasers must be used in these applications.) Radar and lidar are very similar to the ultrasonic sensor which was discussed in Section 3.2.2.3 above. Both also have the problem that the energy incident on the target is reflected in many different directions. (Refer to YOUNG (1973) for a discussion of miniature radar in machine perception applications; or to SKOLNIK (1962) for a general discussion of radar principles.)

3.2.3 ANALYSIS OF SENSOR CONCEPTS

This section contains a qualitative as well as a quantitative analysis of the different sensor concepts identified in Section 3.2.2. (CROSS (1989) and STARKEY (1988) describe similar analysis and trade-off procedures.) The following points are very important regarding the analysis technique used:

a. It is by no means claimed that the technique used can provide absolutely accurate answers. It mainly serves to indicate trends; to ensure that adequate thought was given to the required performance parameters; and to ensure that different concepts are measured against the same standards.

b. The choice of a sensor concept is based on the specific technical performance requirements defined in Section 3.2.1.1; and does not hold for any machine perception system in general.

The ability of each concept to meet the requirements signified by the performance parameters defined in Section 3.2.1, is analyzed in Tables 3.2a through 3.2f. Based on the qualitative analysis presented in the third column of the table, for each performance parameter, the concept is rated with a value between 0 and 5 - as shown in the fourth column of the table. The following ratings are used:

0: the concept is completely **inadequate** to satisfy the requirements;
1: the concept is a **very poor** solution to satisfy the requirements;
2: the concept is a **poor** solution to satisfy the requirements;
3: the concept is a **reasonable / tolerable** solution to satisfy the requirements;
4: the concept is a **good** solution to satisfy the requirements;
5: the concept is an **ideal** solution to satisfy the requirements.

The second column of each table contains the *weight* - as allocated to each performance parameter in Table 3.1. The last column of each table contains the *weighted ratings*, which are the ratings in column 4, weighted by the parameter weights in column 2. The *weighted rating = weight x (rating/5)*. (In this formula, the rating is divided by the maximum rating 5, in order to normalize the answers.)

In order to remove possible bias of the author towards certain concepts, another engineer with extensive experience in such trade-off studies, was asked to repeat the complete trade-off process independently. The two sets of results were very similar, and were combined to form the results shown in Table 3.2.

1	2	3	4	5
Performance parameter	Weight [%]	Qualitative Analysis of Television Cameras as Sensor Concept for a Milking Robot	Quantitative Analysis	
			Rating (0-5)	Weighted rating
Recognition of objects	15	A television camera forms grey-level or colour images of objects in a scene. With a suitable image processor, the presence or absence of objects within a working space can be detected, and objects can be distinguished from one another.	4	12
Localisation of objects	21	Television cameras provide images which are suitable for use by an image processor for two- or three-dimensional localisation of objects (mono or stereo perception). The computational load for localisation calculations can be rather heavy, but appropriate computer architecture can solve this problem.	4	17
Inspection of objects	14	A television camera provides images from which a suitable image processor can derive object characteristics (inspection). Images can also be recorded for later inspection by a human operator.	5	14
Sensor simplicity	9	A television camera is a passive device (i.e. it does not transmit any signals or energy towards the target scene). Although it is a complex device, its operating principles are inherently simple. Although extensive signal processing is required, it will not require the most complex computer hardware which is available today.	4	7
Environmental compatibility	19	A television camera will be negatively influenced by water on its electronics; by dust and dirt on its lens; and by mechanical shocks. It can however be mounted on shock-mounts, in a protective case covered by a durable *light-transparent* front plate, with windscreen wiper-like cleaners.	4	15
Sensing speed	16	A television camera converts incoming light from a scene into signals representing the image, in real-time. The overall sensing speed is reduced however by the amount of signal processing required. However, with ever increasing computational speeds of modern computers, this problem becomes smaller.	4	13
Interfacing	6	The outputs of a television camera are in the form of electrical signals. Therefore interfacing with a signal processor (typically a digital computer) is simple.	5	6
	100			84

TABLE 3.2a: Analysis of television cameras as sensor concept for a milking robot

1	2	3	4	5
Performance parameter	Weight [%]	Qualitative Analysis of an Array of Light Beams as Sensor Concept for a Milking Robot	Quantitative Analysis	
			Rating (0-5)	Weighted rating
Recognition of objects	15	An array of light beams is commonly used as a detection device - and the concept is very suitable for detecting the presence of a cow's udder and teats. It is however not suitable for distinguishing a cow's teats from other similar looking objects (e.g. milking machine pipes) in the perception field.	2	6
Localisation of objects	21	An array of light beams can be used to locate a cow's udder, but it is not very suitable to accurately localise a cow's teats. This is due to the low measurement resolution of such a system. If the resolution is to be *increased, too many* light sources and -receivers will be required. Such a system approaches the principle of a television camera, which effectively has a large array of light intensity detectors.	2	8
Inspection of objects	14	An array of light beams is not suitable at all for inspection of objects, since it is merely a low resolution detection device	0	0
Sensor simplicity	9	An array of light beams is the simplest of all the sensor concepts, since it only requires light emitting diodes (LED's) as transmitters, and photo diodes as receivers set up in a pre-defined configuration. This sensor concept is an active device (it illuminates the scene), but its operating principle is simple; requiring *only* very little signal processing.	5	9
Environmental compatibility	19	An array of light beams will be negatively *influenced by water on its electronics; by dust* and dirt on the optical components; and by mechanical shocks. The transmitters and the receivers can however be mounted on shock-mounts, in protective cases covered by durable *light-transparent* front plates, and with windscreen wiper-like cleaners.	4	15
Sensing speed	16	The detectors in an array of light beams respond in real-time to the presence or absence of objects. Since not much signal processing is required, the device can be very fast.	5	16
Interfacing	6	The outputs of an array of light beams are in the form of electrical signals. Therefore interfacing with a signal processor (typically a digital computer) is simple.	5	6
	100			60

TABLE 3.2b: Analysis of an array of light beams as sensor concept for a milking robot

1	2	3	4	5
Performance parameter	Weight [%]	Qualitative Analysis of Ultrasonic Sensors as Sensor Concept for a Milking Robot	Quantitative Analysis	
			Rating (0-5)	Weighted rating
Recognition of objects	15	An ultrasonic sensor is suitable for providing images to a signal processor, which can be used for the detection of an object's presence or absence within a working space. The images will however in general not be easily distinguishable from that due to other similar looking objects in the scene.	3	9
Localisation of objects	21	Ultrasonic sensors can provide data to a signal processor, which is suitable for two- or three-dimensional localisation of objects (mono or stereo perception). Because it is an active device, it is well suited for determining the range of an object, relative to the sensor (by measuring the time it takes for an ultrasonic pulse to travel from the sensor, to the object, and back to the sensor again). Scattering of pulses away from the target, and consequent reflection from other objects might however negatively influence the accuracy of localisation.	4	17
Inspection of objects	14	External inspection of a cow's teats by means of the images formed by ultrasonic sensors will only be possible on a very limited scale.	1	3
Sensor simplicity	9	Ultrasonic sensors are active devices, but they are based on simple operating principles. Although the signal processing required is not quite as extensive as that for a television camera, the processing burden is also heavy if meaningful results are required. Modern computer technology alleviates this problem however.	4	7
Environmental compatibility	19	An ultrasonic sensor will be negatively influenced by water on its electronics; and by mechanical shocks. Water, dust, and dirt can attenuate or reflect the sound waves before it reaches the target objects. Since it emits sound waves towards the target, it can only be mounted in a protective case if an *ultrasonic-transparent* cover is used on the case.	4	15
Sensing speed	16	An ultrasonic sensor can provide signals regarding a scene, to a signal processor in real-time. The overall sensing speed is reduced however by the amount of signal processing required. However, with ever increasing computational speeds of modern computers, this problem becomes smaller.	4	13
Interfacing	6	The outputs of an ultrasonic sensor are in the form of electrical signals. Therefore interfacing with a signal processor (typically a digital computer) is simple.	5	6
	100			70

TABLE 3.2c: Analysis of ultrasonic sensors as sensor concept for a milking robot

1	2	3	4	5
Performance parameter	Weight [%]	Qualitative Analysis of Tactile Sensors as Sensor Concept for a Milking Robot	Quantitative Analysis	
			Rating (0-5)	Weighted rating
Recognition of objects	15	A tactile sensor can provide adequate signals to a signal processor, for the detection of the presence or absence of an object within a working space - provided that the sensor can touch the object. Since a tactile sensor is generally used for sensing forces when it touches an object, this type of sensor is not very suitable for distinguishing the teats from other objects in the perception field.	2	6
Localisation of objects	21	Because a tactile sensor relies on contact between the sensor and the objects, it is not very suitable as the main sensor for (remotely) localising a cow's teats. It is more suitable to localise an object relative to a moving arm, with a tactile sensor on it.	2	8
Inspection of objects	14	Meaningful inspection of a cow's teats will not be possible by means of tactile sensors.	0	0
Sensor simplicity	9	The operating principle of tactile sensors is simple. This concept can however not easily be used as a stand-alone sensor for a milking robot, since the sensor relies on contact with the object to be sensed. That implies that the sensor must be moved around in the working space where the cow's teats can possibly be - which makes the global operation of this concept complex. (This type of sensor is therefore more suitable to be used as an *auxiliary* sensor, rather than as the main sensor for the milking robot.)	1	2
Environmental compatibility	19	A tactile sensor will be negatively influenced by water on its electronics. Although moderate quantities of dust will not have a severe influence on the sensor, dirt on its surface can cause distorted force distributions on the sensor - and thus wrong measurements. Furthermore, mechanical shocks directly on the sensor surface will cause disturbances in the sensor's output.	4	15
Sensing speed	16	Although the tactile sensor converts force to electrical signals in real-time, its sensing speed is slowed down by the requirement that the sensor must move around.	2	6
Interfacing	6	The outputs of tactile sensors are in the form of electrical signals. Therefore interfacing with a signal processor (typically a digital computer) is simple.	5	6
	100			43

TABLE 3.2d: <u>Analysis of tactile sensors as sensor concept for a milking robot</u>

1	2	3	4	5
Performance parameter	Weight [%]	Qualitative Analysis of Infrared Sensors as Sensor Concept for a Milking Robot	Quantitative Analysis	
			Rating (0-5)	Weighted rating
Recognition of objects	15	An infrared sensor is suitable for providing images to an image processor, which can be used for the detection of an object's presence or absence within a working space - provided that adequate thermal differences exist between the target object and other objects. If a cow's teats and udder are warmer than other objects in the working space, infrared sensors are suitable for distinguishing the teats and the udder from the environment. Such temperature differences are however not guaranteed.	3	9
Localisation of objects	21	Infrared sensors can provide data to a signal processor, which is suitable for two- or three-dimensional localisation of objects (mono or stereo perception). Since temperature differences, adequate to ensure proper thermal images of a cow's teats, cannot be guaranteed (refer to the discussion under 3.2.2.5 above) localisation of teats by means of an infrared sensor might be difficult.	3	13
Inspection of objects	14	The temperature of a teat with a cut, or an ulcer on the surface, or with mastitis infection, will in general be higher than that of a healthy teat. Extreme differences between a cow's individual teat temperatures are thus indicative of teat health problems, and can be detected by means of an infrared sensor. (Mastitis detection can however be done more easily by means of measuring the electrical conductivity of the milk - refer to *Dairy Farming* in Appendix G for literature references in this regard.) Thermal images can also be recorded for later inspection by a human operator.	2	6
Sensor simplicity	9	An infrared sensor converts heat emitted from a scene, to electrical signals. It is a passive device; and although it is a complex device, its operating principles are inherently simple. Although extensive signal processing is required, it is not beyond the abilities of modern computer technology.	4	7
Environmental compatibility	19	An infrared sensor will be negatively influenced by water on its electronics; by dust and dirt on its lens; and by mechanical shocks. It can however be mounted on shock-mounts, in a protective case covered by a durable *infrared-transparent* front plate, with windscreen wiper-like cleaners.	4	15
Sensing speed	16	An infrared sensor can provide signals regarding a scene, to a signal processor in real-time. The overall sensing speed is reduced however by the amount of signal processing required. However, with ever increasing computational speeds of modern computers, this problem becomes smaller.	4	13
Interfacing	6	The outputs of an infrared sensor are in the form of electrical signals. Therefore interfacing with a signal processor (typically a digital computer) is simple.	5	6
	100			69

TABLE 3.2e: Analysis of infrared sensors as sensor concept for a milking robot

1	2	3	4	5
Performance parameter	Weight [%]	Qualitative Analysis of Miniature Radar & Lidar as Sensor Concepts for a Milking Robot	Quantitative Analysis	
			Rating (0-5)	Weighted rating
Recognition of objects	15	Both miniature radar and lidar are suitable for providing signals to a signal processor, which can be used for the detection of an object's presence or absence within a working space. The images formed by miniature radar or by lidar will however in general not be easily distinguishable from that due to other similar looking objects in the scene.	2	6
Localisation of objects	21	Both miniature radar and lidar can provide data to a signal processor, which is suitable for two- or three-dimensional localisation of objects. Because both are active devices, they are well suited for determining the range of an object, relative to the sensor (by measuring the time it takes for a radio or light pulse to travel from the sensor, to the object, and back to the sensor again). Scattering of pulses away from the target, and consequent reflection from other objects might however negatively influence the accuracy of localisation.	3	13
Inspection of objects	14	External inspection of a cow's teats by means of the images formed by miniature radar or lidar will only be possible *on a very limited scale.*	1	3
Sensor simplicity	9	Both miniature radar and lidar are active devices, but they are based on simple operating principles. In order to extract useful information, extensive signal processing is required. Modern computer technology makes this possible however.	4	7
Environmental compatibility	19	Both miniature radar and lidar will be negatively influenced by water on its electronics; and by mechanical shocks. Water, dust, and dirt can absorb or reflect the transmitted energy on its way between the sensor and the target (in either direction). Since radar emits radio waves towards the target, it can only be mounted in a protective case if a *radar-transparent* cover is used on the case. Similarly, lidar transmits light towards the target, and it can thus only be mounted in a protective case if a *light-transparent* cover is used on the case.	4	15
Sensing speed	16	Both miniature radar and lidar can provide signals regarding a scene, to a signal processor in real-time. The overall sensing speed is reduced however by the amount of signal processing required. However, with ever increasing computational speeds of modern computers, this problem becomes smaller.	4	13
Interfacing	6	The outputs of both a miniature radar device and of lidar are in the form of electrical signals. Therefore interfacing with a signal processor (typically a digital computer) is simple.	5	6
	100			63

TABLE 3.2f: Analysis of miniature radar & lidar as sensor concepts for a milking robot

1	2	3	4	5
Performance parameter	Weight [%]	Qualitative Analysis of Infrared Sensors as Sensor Concept for a Milking Robot	Quantitative Analysis	
			Rating (0-5)	Weighted rating
Recognition of objects	15	An infrared sensor is suitable for providing images to an image processor, which can be used for the detection of an object's presence or absence within a working space - provided that adequate thermal differences exist between the target object and other objects. If a cow's teats and udder are warmer than other objects in the working space, infrared sensors are suitable for distinguishing the teats and the udder from the environment. Such temperature differences are however not guaranteed.	3	9
Localisation of objects	21	Infrared sensors can provide data to a signal processor, which is suitable for two- or three-dimensional localisation of objects (mono or stereo perception). Since temperature differences, adequate to ensure proper thermal images of a cow's teats, cannot be guaranteed (refer to the discussion under 3.2.2.5 above) localisation of teats by means of an infrared sensor might be difficult.	3	13
Inspection of objects	14	The temperature of a teat with a cut, or an ulcer on the surface, or with mastitis infection, will in general be higher than that of a healthy teat. Extreme differences between a cow's individual teat temperatures are thus indicative of teat health problems, and can be detected by means of an infrared sensor. (Mastitis detection can however be done more easily by means of measuring the electrical conductivity of the milk - refer to *Dairy Farming* in Appendix G for literature references in this regard.) Thermal images can also be recorded for later inspection by a human operator.	2	6
Sensor simplicity	9	An infrared sensor converts heat emitted from a scene, to electrical signals. It is a passive device; and although it is a complex device, its operating principles are inherently simple. Although extensive signal processing is required, it is not beyond the abilities of modern computer technology.	4	7
Environmental compatibility	19	An infrared sensor will be negatively influenced by water on its electronics; by dust and dirt on its lens; and by mechanical shocks. It can however be mounted on shock-mounts, in a protective case covered by a durable *infrared-transparent* front plate, with windscreen wiper-like cleaners.	4	15
Sensing speed	16	An infrared sensor can provide signals regarding a scene, to a signal processor in real-time. The overall sensing speed is reduced however by the amount of signal processing required. However, with ever increasing computational speeds of modern computers, this problem becomes smaller.	4	13
Interfacing	6	The outputs of an infrared sensor are in the form of electrical signals. Therefore interfacing with a signal processor (typically a digital computer) is simple.	5	6
	100			69

TABLE 3.2e: Analysis of infrared sensors as sensor concept for a milking robot

1	2	3	4	5
Performance parameter	Weight [%]	Qualitative Analysis of Miniature Radar & Lidar as Sensor Concepts for a Milking Robot	Quantitative Analysis	
			Rating (0-5)	Weighted rating
Recognition of objects	15	Both miniature radar and lidar are suitable for providing signals to a signal processor, which can be used for the detection of an object's presence or absence within a working space. The images formed by miniature radar or by lidar will however in general not be easily distinguishable from that due to other similar looking objects in the scene.	2	6
Localisation of objects	21	Both miniature radar and lidar can provide data to a signal processor, which is suitable for two- or three-dimensional localisation of objects. Because both are active devices, they are well suited for determining the range of an object, relative to the sensor (by measuring the time it takes for a radio or light pulse to travel from the sensor, to the object, and back to the sensor again). Scattering of pulses away from the target, and consequent reflection from other objects might however negatively influence the accuracy of localisation.	3	13
Inspection of objects	14	External inspection of a cow's teats by means of the images formed by miniature radar or lidar will only be possible on a very limited scale.	1	3
Sensor simplicity	9	*Both miniature radar and lidar are active devices, but they are based on simple operating principles. In order to* extract useful information, extensive signal processing is required. Modem computer technology makes this possible however.	4	7
Environmental compatibility	19	Both miniature radar and lidar will be negatively influenced by water on its electronics; and by mechanical shocks. Water, dust, *and dirt can absorb or reflect the transmitted energy on its way between the sensor and the target* (in either direction). Since radar emits radio waves towards the target, it can only be mounted in a protective case if a *radar-transparent* cover is used on the case. Similarly, lidar transmits light towards the target, and it can thus only be mounted in a protective case if a *light-transparent* cover is used on the case.	4	15
Sensing speed	16	*Both miniature radar and lidar can provide signals regarding a scene, to a signal processor in real-time.* The overall sensing speed is reduced however by the amount of signal processing required. However, with ever increasing computational speeds of modern computers, this problem becomes smaller.	4	13
Interfacing	6	The outputs of both a miniature radar device and of lidar are in the form of electrical signals. Therefore interfacing with a *signal processor (typically a digital computer) is simple.*	5	6
	100			63

TABLE 3.2f: Analysis of miniature radar & lidar as sensor concepts for a milking robot

Performance Parameters	Weight [%]	Television Camera	Array of Light Beams	Ultrasonic Sensor	Tactile Sensor	Infrared Sensor	Miniature Radar & Lidar
Recognition of objects	15	12	6	9	6	9	6
Localisation of objects	21	17	8	17	8	13	13
Inspection of objects	14	14	0	3	0	6	3
Sensor simplicity	9	7	9	7	2	7	7
Environmental compatibility	19	15	15	15	15	15	15
Sensing speed	16	13	16	13	6	13	13
Interfacing	6	6	6	6	6	6	6
TOTAL RATING [%]	100	84	60	70	43	69	63

TABLE 3.3: Summary of trade-off results for different sensor concepts for the milking robot

3.2.4 CONCLUSIONS FROM THE SENSOR ANALYSIS

From the results of the trade-off presented in Section 3.2.3, it is concluded that a **television camera** is the most suitable sensor concept to satisfy the specific technical performance requirements, defined in Section 3.2.1 for a milking robot's main sensor.

From the results it is clear that an ultrasonic sensor, or an infrared sensor should also provide good results in such a robotic system. The main differences between the three "best" sensor concepts (refer to Table 3.3) are in its *recognition* and its *inspection* capabilities. Both these characteristics are considered to be secondary requirements however (refer to the first paragraph of Chapter 3). This finding explains the good results obtained by other researchers making use of ultrasonic sensors (refer to Table 2.1).

From Table 3.3, the following conclusions are reached regarding the other three sensor concepts:

a. The **array of light beams** is rejected mainly because of its poor abilities for accurate localisation, and for its lack of inspection capabilities.

b. The **tactile sensor** fared the worst, and is rejected mainly because of its poor localisation abilities, it lack of inspection abilities, and the requirement to make contact with the target object.

c. **Miniature Radar & Lidar** - although better than the latter two concepts - have poor inspection capabilities, and recognition capabilities.

In order to best satisfy the defined performance requirements, a television camera will be used as the basis for the rest of this research project. (In follow-up work, one or more of the other sensor concepts might be useful as auxiliary sensors for the milking robot.)

3.3 COMMENTS ON THE USE OF TELEVISION CAMERAS FOR MACHINE PERCEPTION

A television camera can be characterized in terms of two transformations:

a. A geometric transformation, which consists of a transformation from the three-dimensional coordinates of points in a scene (world coordinates), to a two-dimensional projection of the points (image coordinates). In order to characterise the geometric transformation, the frames of reference (world- and image coordinates) must first of all be well defined. Secondly, a camera model must be defined, and the camera must be calibrated within the chosen frames of reference, involving:
   i. The development of a mathematical model of the camera's geometric transformation characteristics; and
   ii. The determination of the parameters of the camera model.

b. An electronic transformation, involving a transformation from light intensity, to an array of electronic signals - typically a 512 x 512 array of 8 bit grey scale values. (Refer to FLORY (1985) and the Electro-Optics Handbook of RCA (1974), for detailed discussions of the electronic transformation in television cameras.)

Appendix A contains a brief description of an experimental machine perception subsystem - making use of television cameras - for a milking robot. The system described there was used extensively for experimental verification of different concepts.

3.4 THE SIGNAL PROCESSOR

3.4.1 INTRODUCTORY SIGNAL PROCESSING CONCEPTS

Since a **television camera** was chosen as the main sensor for the machine perception subsystem of the milking robot, only **image processing** concepts are discussed in this section. The primary task of the milking robot's image processor (implemented by means of computer hardware and software) is to derive a computerized description of the spatial positions of the endpoints of a cow's four teats, in terms of some frame of reference (the world coordinates). This process is termed **scene description** - which can be considered as the inverse of the sensor's image formation process.

The inputs for the scene description process are the image coordinates of certain features in one or more images of a real-world scene. (The image coordinates are determined as described in Section 3.4.4 below.) The output of the scene description process is a computerized description of the pre-defined scene features - in terms of either two-dimensional, or three-dimensional world coordinates. For a milking robot, the manipulator's controller (refer to Section 4.5) will command the manipulator, based on the scene description results.

3.4.2 EFFECTS OF ERRORS IN A MILKING ROBOT'S SCENE DESCRIPTION

Before scene description and its related processes are discussed, the effects of errors in the calculated positions of the teat endpoints (i.e. of errors in the scene description process), on the functioning of a milking robot, are first addressed.

Consider the possible errors in the calculated positions of a cow's teat endpoints, as shown in Figure 3.1.

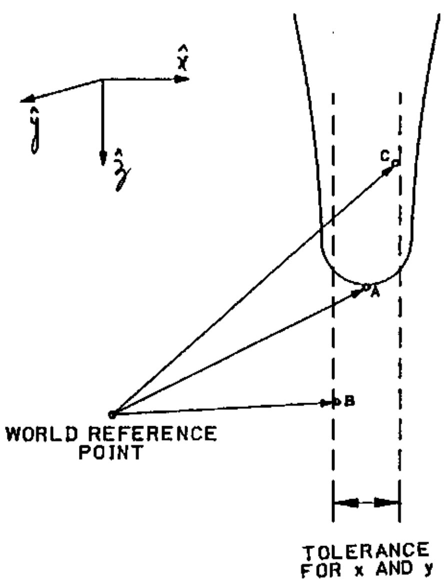


FIGURE 3.1: <u>Possible errors in the calculated teat position</u>

a. If the position reference value for the manipulator and the teatcup (i.e. the calculated coordinates of the teat's endpoint) is point A in Figure 3.1, then the manipulator will take the teatcup to the right initial position. The teatcup must however still be moved upwards from point A, in order to allow the teat to be sucked into the teatcup.

b. If the position reference value for the manipulator and the teatcup is point B in Figure 3.1, then the manipulator will take the teatcup too low initially, and the teat will only be sucked into the teatcup if the error in the horizontal plane is not too large, and if the teatcup is moved upwards by the manipulator.

c. If the position reference value for the manipulator and the teatcup is point C in Figure 3.1, and if the manipulator takes the teatcup's opening straight to that point, the teat will not enter the teatcup. (Unless the teatcup's starting point is exactly below the teat.) Therefore, no errors resulting in the calculated position of a teat's endpoint being higher than the real position, can be tolerated in the machine perception subsystem.

d. A very important aspect which becomes clear from this analysis is that a two-stage manipulator action is required: it must first bring the opening of the teatcup to (just below) the teat's endpoint; and then it must move upwards in order that the teat can be sucked in by the teatcup. (This aspect is addressed again in Chapter 4.)

In order to determine the tolerance in the horizontal plane (i.e. the maximum horizontal deviation of point B in Figure 3.1, from the teat's centreline), some experiments were carried out:

a. Twenty Friesian cows in different lactations, and in different stages of their lactations were randomly chosen from a herd of about 300 cows. (That provided a good sample of different teat shapes, sizes, and orientations. These characteristics are however difficult to record or describe scientifically.)

b. For each teat it was tried to attach a vertically held teatcup, with a difference of 20 mm in the horizontal plane, between the teat's centreline and that of the teatcup. If this attempt was unsuccessful, it was repeated with a difference of 15 mm. If this attempt was unsuccessful, 10 mm was tried; then 5 mm; and eventually 0 mm. (Distances were measured with an accuracy of about 2 mm, by means of a measuring tape.)

c. The following results were obtained:
   i. no teatcups could be attached with

differences in the horizontal plane of 20 mm;

ii. for 9 teats, the teatcup could be attached, with a difference of 15 mm in the horizontal plane;

iii. for 67 teats, the teatcup could be attached, with a difference of 10 mm in the horizontal plane; and

iv. for 4 teats, the teatcup could only be attached, with a difference of 5 mm in the horizontal plane.

d. Furthermore, it was found that the teatcups could be attached with differences in the centreline orientations in the order of about 45°. (This is due to the typical tapered form of a cow's teats, and due to the suction of the milking machine's vacuum system.)

Based on the above results, it was decided to allow for an error of up to 10 mm in the horizontal plane, during the design process. Since the errors due to the milking robot's two subsystems (machine perception and manipulator) are completely independent, the total milking robot error will be the root-sum-square value of the individual errors. (Refer to DOEBELIN (1983, p.63) for the theory of error calculations.) An elaborate error budget (which is normally done as part of the design of accurate control systems), was not done for the milking robot. The error of the manipulator subsystem can (ideally) be eliminated by proper design of the arm and its control system (except for small errors as discussed in Section 4.2.1.4). It is therefore anticipated that the machine perception subsystem will be the main contributor to the overall system error. If an allowable error of 9 mm is allocated to the machine perception subsystem, an error of 4,3 mm can still be tolerated for the manipulator, before the total root-sum-square error $(9^2 + 4{,}3^2)^{1/2}$ becomes 10 mm.

3.4.3 SCENE DESCRIPTION CONCEPTS FOR THE MILKING ROBOT

3.4.3.1 TWO-DIMENSIONAL SCENE DESCRIPTION

3.4.3.1.1 Background

Two-dimensional scene description is defined as the transformation from the two-dimensional image coordinates of a point, to a description of the point in terms of two-dimensional world coordinates (i.e. one dimension in the world coordinate system - for example scene depth - is discarded). Two-dimensional scene description makes use of the image derived from a single camera. Two-dimensional scene description holds a number of important advantages, which led to the feasibility of this concept being investigated for the milking robot:

a. Cheaper equipment is required (only one camera, and one image processor).

b. Faster image processing is possible (simpler algorithms).

c. It was concluded in Section 3.4.2 above that no calculation errors resulting in the calculated position of a teat's endpoint being higher than the real position, can be tolerated; and that the teatcup will have to be moved upwards in any case after the teat's endpoint had been reached. Should it be possible to localise a cow's teat endpoints in two dimensions (i.e. only in the horizontal plane), the manipulator could be used to move the teatcups to the correct positions in the horizontal plane, and then to move it upwards, until the teats are sucked in by the teatcups. This situation is similar to that for points A and B in Figure 3.1; while the problem associated with point C in Figure 3.1 is eliminated.

(Occlusion of teats by teatcups already attached to the cow's other teats, is a potential problem. This is true for any type of sensor however. Since the teats will be viewed from below with two-dimensional scene description, the problem of occlusion can be alleviated by attaching the teatcups in a well defined order. If the manipulator is on the right hand side of the stall - i.e. the teatcups' pipes extrude to the cow's right, then a suitable order for attaching the teatcups can be: right rear, right front, left rear, left front.)

3.4.3.1.2 Experimental results obtained with two-dimensional scene description

In order to verify the approach discussed above, some two-dimensional scene description experiments were performed with a number of points in a plane. As a first approach, it was assumed that a cow's teat endpoints are nominally in the same horizontal plane. A very simple relationship between the two-dimensional world coordinates (x,y) of points in a plane and their corresponding two-dimensional image coordinates (U,V), was derived empirically:

$$x = m_1U + c_1 \quad (3.1)$$
$$y = m_2V + c_2 \quad (3.2)$$

In order to characterise the two-dimensional camera model (i.e. to determine m_1, m_2, c_1, and c_2), nine points were marked on a flat plate, and their two-dimensional world coordinates determined. The bottom left corner of the plate was chosen as the reference point for the two-dimensional world coordinates. In this case, the x-coordinate was defined to the right, while the y-coordinate was defined upwards.

The points marked on the plate were filmed with a television camera (with its image plane parallel to the plate), and each point's image coordinates were determined from a video image of the points. The top left corner of the video monitor was chosen as reference point for the image coordinates. The U-coordinate was defined to the right, while the V-coordinate was defined downwards. (The image coordinates were determined by means of a movable cursor on the graphics screen.) The results of this process are shown in Table 3.4. The measured world and image coordinates of the first four points in Table 3.4 (*Measurement point number 1, 2, 3, 4*) were used in a PC-MATLAB program (CAL2D.M - refer to Appendix E), in order to calibrate the camera, rendering the following relationship between the two-dimensional world coordinates (x,y) of a point, and its corresponding two-dimensional image coordinates (U,V):

$$x = 1{,}1526\ U - 108{,}0972 \quad (3.3a)$$
$$y = -0{,}7574\ V + 242{,}4592 \quad (3.3b)$$

The last five points in Table 3.4 were also used in the PC-MATLAB program CAL2D.M (Appendix E) to verify the camera model in (3.3). The results of this verification process are shown in Table 3.5 - with the following symbols being used in the tables:-

- U_m measured U-coordinates - Table 3.4
- V_m measured V-coordinates - Table 3.4
- x_c calculated x-coordinates [mm] - eq.(3.3a)
- x_m measured x-coordinates [mm] - Table 3.4
- x_e difference between calculated- and measured x-coordinates: $x_e = x_c - x_m$
- y_c calculated y-coordinates [mm] - eq.(3.3b)
- y_m measured y-coordinates [mm] - Table 3.4
- y_e difference between calculated- and measured y-coordinates: $y_e = y_c - y_m$
- d absolute position error in the x-y plane [mm]; $d = (x_e^2 + y_e^2)^{1/2}$

Measurement point number	Measured world coordinates [mm]		Measured image coordinates [pixels]	
	x_m	y_m	U_m	V_m
1	228	104	290	182
2	100	100	181	188
3	152	43	226	262
4	322	70	374	230
5	360	178	404	90
6	230	159	292	110
7	237	212	297	41
8	115	192	192	71
9	38	246	129	0

TABLE 3.4: <u>World- and image coordinates of nine two-dimensional points</u>

Measurement point number	U_m [pixels]	V_m [pixels]	x_c [mm]	x_m [mm]	x_e [mm]	y_c [mm]	y_m [mm]	y_e [mm]	d [mm]
5	404	90	358	360	-2	174	178	-4	4,47
6	292	110	228	230	-2	159	159	0	2,00
7	297	41	234	237	-3	211	212	-1	3,16
8	192	71	113	115	-2	189	192	-3	3,61
9	129	0	41	38	-3	242	246	-4	5,00

TABLE 3.5: Evaluation of the two-dimensional camera model derived in (3.3)

From the results in Table 3.5 it is concluded that two-dimensional localisation of objects by means of machine vision (under laboratory conditions), renders good results.

3.4.3.1.3 Experimental results obtained with two-dimensional localisation of a cow's teats

With the good results obtained by means of two-dimensional object localisation under laboratory conditions, the approach was tried on a cow's teats. The first problem was to obtain images from directly below the udders. By making use of an inclined mirror, this problem could be overcome. Under practical conditions, this solution will have certain problems associated with positioning the mirror, and with keeping it clean. At this stage no attempt was made to propose final solutions to these problem areas, since another more serious problem occurred with the two-dimensional localisation of a cow's teats: for all the cows used for the experiment, the machine vision system could not distinguish between the teats and the udder. This is due to the cows having udders and teats of the same colour. Variations in lighting was tried as a possible solution to this problem. The shades cast by the teats onto the udders could under certain conditions be used to localise the teat roots (i.e. the positions where the teats are attached to the udder). The use of shades was however found unsatisfactory - and was therefore discarded - for three reasons:

a. The (x,y) coordinates of the teat roots do not necessarily correspond to that of the teat endpoints.

b. Too many uncertainties are introduced, because the shades depend on many variables - such as the shapes and sizes of the teats; the position of the light source; the spatial attitude of the cow; the cow's leg length; etc.

c. It is limited to cows with white or near-white udders, because the teats' shades are invisible on dark udders.

3.4.3.1.4 Conclusions on the feasibility of two-dimensional scene description for the milking robot

Two-dimensional scene description holds several advantages, and was found to be accurate for the localisation of objects in two dimensions (under laboratory conditions, and depending on the nature of the objects). The concept - making use of a television camera and an image processor - was however found unfeasible for two-dimensional localisation of a cow's teats. The main reason for this is the difficulty experienced by the machine vision system to distinguish between a cow's teats and her udder (due to the teats and the udder being the same colour), when viewing the udder and teats directly from below.

The concept of two-dimensional localisation of a cow's teats by means of machine vision was thus discarded (after many unsuccessful attempts to implement it). Because of its potential advantages, the concept should however not be written off completely, but it should be researched further in future.

3.4.3.2 THREE-DIMENSIONAL SCENE DESCRIPTION

3.4.3.2.1 Background

Three-dimensional scene description is defined as the transformation from two different sets of two-dimensional image coordinates of a point (a stereo pair), to a description of the point in terms of three-dimensional world coordinates. Three-dimensional scene description is derived from two cameras (or one moving camera, or one camera plus an extra sensor). This process combines the outputs of two two-dimensional scene descriptions, in order to form one three dimensional scene description - and is often based on the principles of human stereo vision.

(Refer to JORDAN & BOVIK (1988); KANADE (1983); MARR & POGGIO (1979); SHAH et al (1989); VILLEE (1977, p.538); WAXMAN & DUNCAN (1986); and YAKIMOVSKY & CUNNINGHAM (1978) for discussions on human vision.)

The main advantage of three-dimensional scene description is that both the position and the orientation of an object can be described in a three-dimensional frame of reference. Due to the need for two cameras and two signal processors, the equipment for this method is relatively expensive, however.

3.4.3.2.2 Mathematical models for three-dimensional scene description

In order to evaluate three-dimensional scene description for the milking robot, different models for the geometric transformation performed by television cameras, were analyzed (refer to GOUWS (1989b)). The models analyzed included triangulation (e.g. DUDA & HART (1973, pp.398-401)); and the camera models presented by BALLARD & BROWN (1982, p.484); DUDA & HART (1973, pp.382-392); and YAKIMOVSKY & CUNNINGHAM (1978). From the analysis of the different techniques, it was decided to concentrate on the method proposed by BALLARD & BROWN (1982) - mainly because of its relative simplicity. (The details of this method is discussed below - more elaborately than the discussion by BALLARD & BROWN though.)

3.4.3.2.2.1 Simple image formation

A simple image formation process is shown in Figure 3.2 - with the imaging plane artificially placed between the object and the camera's focus point (for the sake of clarity). From simple trigonometry, the relationship between the object's world coordinates (x,y,z) and its image coordinates (U,V), is the following:

$$V = z.f/(f + x) \quad (3.4a)$$
$$U = y.f/(f + x) \quad (3.4b)$$

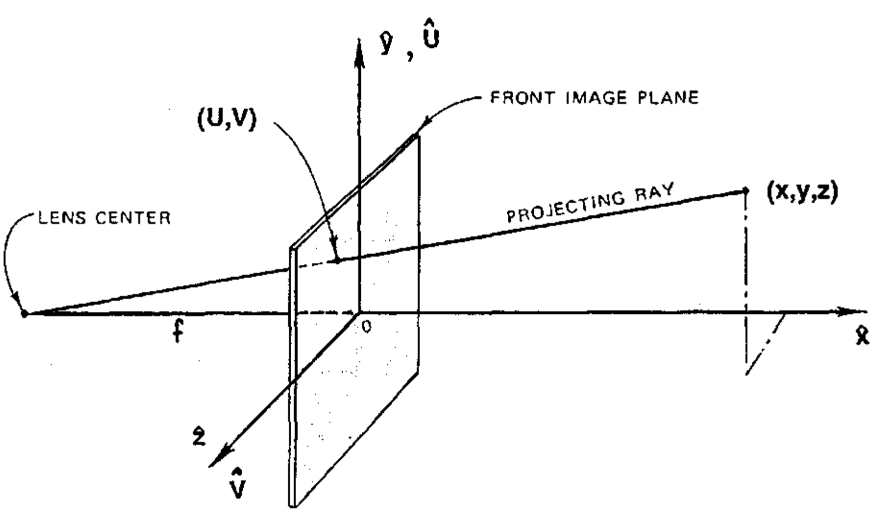


FIGURE 3.2: Simple image formation

Since division by (f + x) is used in (3.4), the two equations do not represent a linear relationship between image and world coordinates. These equations can be linearised however, by making use of *homogeneous coordinates*. Homogeneous coordinates of an object with world coordinates (x,y,z), are defined as (x',y',z',w) - refer to NEVATIA (1982, pp.31-37) and ROBERTS (1965) - such that:

$$x = x'/w \quad (3.5a)$$
$$y = y'/w \quad (3.5b)$$
$$z = z'/w \quad (3.5c)$$

The homogeneous coordinates of the object's image point - with image coordinates (U,V) - are defined as (u,v,t), such that:

$$U = u/t \quad (3.5d)$$
$$V = v/t \quad (3.5e)$$

Because of the definitions in (3.5), the values of *w* and *t* can be arbitrarily chosen. A common choice is w = 1 - resulting in homogeneous coordinates (x,y,z,1). The value of *t* can then be chosen such as to linearise the camera's equations - which is the case if t = (f + x)/f is chosen, and substituted into equation (3.4).

From this chosen value of *t*, the image formation process shown in Figure 3.2, can be written as in equation (3.6a) - which represents a simple linear relationship (mathematical camera model) between the image coordinates (U,V) and the world coordinates (x,y,z) of an object. Equation (3.6b) represents a more concise form of the camera model.

3.4.3.2.2.2 Generalized model of image formation

The camera model shown in (3.6a) makes use of the same reference point for both the world- and the image coordinates (refer to Figure 3.2). This is often unpractical. A more general camera model can however be derived, which describes a television camera's geometric transformation, from a three-dimensional world point (x,y,z) - measured in terms of a world reference point; to a two-dimensional image point (U,V) - measured in terms of an independent image reference point. In this case, matrix $\underline{C}$ as defined in (3.6a) and (3.6b), is generalized to the form shown in (3.6c). The twelve camera parameters in (3.6c) incorporate scaling, and relative rotation and translation between the two frames of reference. The elements C_m in (3.6c) therefore consist of directional cosine terms - GOLDSTEIN (1978, p.99); as well as terms accounting for relative translation between the two frames of reference.

$$[x \ y \ z \ 1]\begin{bmatrix} 0 & 0 & \frac{1}{f} \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} Ut \\ Vt \\ t \end{bmatrix} = \begin{bmatrix} u \\ v \\ t \end{bmatrix} \quad (3.6a)$$

$$[x \ y \ z \ 1]\,\underline{C} = \begin{bmatrix} u \\ v \\ t \end{bmatrix} \quad (3.6b)$$

$$\underline{C} = \begin{bmatrix} C_1 & C_5 & C_9 \\ C_2 & C_6 & C_{10} \\ C_3 & C_7 & C_{11} \\ C_4 & C_8 & C_{12} \end{bmatrix} \quad (3.6c)$$

Equations (3.6b) and (3.6c) can then be expanded and manipulated as follows:

$$xC_1 + yC_2 + zC_3 + C_4 = u = Ut \qquad (3.7a)$$
$$xC_5 + yC_6 + zC_7 + C_8 = v = Vt \qquad (3.7b)$$
$$xC_9 + yC_{10} + zC_{11} + C_{12} = t \qquad (3.7c)$$

By substituting the expression for t, in (3.7c), into (3.7a) and (3.7b), the following two equations are derived:

$$xC_1 + yC_2 + zC_3 + C_4 - UxC_9 - UyC_{10} - UzC_{11} - UC_{12} = 0 \qquad (3.8a)$$

$$xC_5 + yC_6 + zC_7 + C_8 - VxC_9 - VyC_{10} - VzC_{11} - VC_{12} = 0 \qquad (3.8b)$$

In order to determine the values of the twelve elements in matrix $\underline{C}$ (i.e. to "calibrate the camera"), twelve equations - in the form of (3.8a) and (3.8b) - are required. From (3.8) it is obvious that there are two equations resulting for each transformation from a world point (x,y,z), to an image point (U,V). In order to derive twelve equations, the world- and image coordinates of six points in a scene must thus be known.

If a number of equations such as (3.8) are written in matrix format such as (3.9), it is noted that $\underline{H} = \underline{0}$ - representing a homogeneous matrix equation. Standard matrix techniques can therefore not be used to solve for $\underline{C}$.

$$\underline{F}\,\underline{C} = \underline{H} \qquad (3.9)$$

KREYSZIG (1979, p.810) suggests the use of Jacobi iteration or Gauss-Seidel iteration for solving a system of linear equations in the form of (3.9), with $\underline{H} = \underline{0}$. In order to ensure that the iteration will converge, there are specific requirements regarding the choice of initial values for the iteration process. In this project, the author was unable to find suitable initial values to ensure a converging iteration.

It is suspected that a similar problem was experienced by BALLARD & BROWN (1982), who solved the problem through scaling of matrix $\underline{C}$ such that $C_{12} = 1$. This scaling is allowable, since the three equations in (3.7) can be divided by C_{12}, without changing the nature of the equations. This is a characteristic of the homogeneous coordinate system, where the scale factor is arbitrarily chosen - refer to ROBERTS (1965) and SID-AHMED & BORAIE (1990). Equations (3.8a) and (3.8b) can be rewritten to (3.10). (The subscripts 1,2,...,n indicate *n* world points, which are transformed to their corresponding image coordinates through equation (3.10).)

In order to calibrate a specific camera (i.e. to determine the elements of $\underline{C}$), the camera is used to transform the known three-dimensional world coordinates of at least six world points to their corresponding two-dimensional image coordinates. After determination of the image coordinates, the values of (x,y,z) and (U,V) are substituted into (3.10).

$$\begin{bmatrix} x_1 & y_1 & z_1 & 1 & 0 & 0 & 0 & 0 & -U_1x_1 & -U_1y_1 & -U_1z_1 \\ 0 & 0 & 0 & 0 & x_1 & y_1 & z_1 & 1 & -V_1x_1 & -V_1y_1 & -V_1z_1 \\ x_2 & y_2 & z_2 & 1 & 0 & 0 & 0 & 0 & -U_2x_2 & -U_2y_2 & -U_2z_2 \\ 0 & 0 & 0 & 0 & x_2 & y_2 & z_2 & 1 & -V_2x_2 & -V_2y_2 & -V_2z_2 \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ x_n & y_n & z_n & 1 & 0 & 0 & 0 & 0 & -U_nx_n & -U_ny_n & -U_nz_n \\ 0 & 0 & 0 & 0 & x_n & y_n & z_n & 1 & -V_nx_n & -V_ny_n & -V_nz_n \end{bmatrix} \begin{bmatrix} C_1 \\ C_2 \\ C_3 \\ C_4 \\ \dots \\ \dots \\ \dots \\ C_{10} \\ C_{11} \end{bmatrix} = \begin{bmatrix} U_1 \\ V_1 \\ U_2 \\ V_2 \\ \dots \\ \dots \\ U_n \\ V_n \end{bmatrix} \qquad (3.10)$$

Matrix $\underline{F}$ - as defined by (3.9) and (3.10) - is however not square, and consequently $\underline{C}$ cannot be determined from $\underline{C} = \underline{F}^{-1}\,\underline{H}$. In order to overcome this problem, the pseudo-inverse $\underline{F}^{*}$ of a rectangular matrix $\underline{F}$ is defined as in (3.11).

$$\underline{F}^{*} = (\underline{F}^{T}\underline{F})^{-1}\underline{F}^{T} \qquad (3.11)$$

This definition is then used in order to determine the camera parameters $\underline{C} = \underline{F}^{*}\,\underline{H}$, from (3.10). (If more than six sets of (x,y,z) and (U,V) are used, it results in an overdetermined set of linear equations, which can also be solved by means of the pseudo-inverse technique.)

3.4.3.2.2.3 Scene description

The aim of the camera calibration process was to determine the camera parameters $\underline{C}$, from which the world coordinates (x,y,z) of a point can be calculated - if the point's image coordinates (U,V) are known. Since the geometric transformation is three-dimensional to two-dimensional, information is lost during the television camera's transformation from a world point (x,y,z), to an image point (U,V). Due to this lost information, the reverse transformation (from an image point (U,V) to a world point (x,y,z)) cannot be done completely by means of only one camera. If another camera is however added - in a stereo vision setup - this problem is overcome.

Once the camera parameters C_1, C_2, ..., C_{11} (remember, through appropriate scaling $C_{12} = 1$) had been determined, three possible routes can be followed in order to determine the world coordinates (x,y,z) of a point, from a stereo pair of image coordinates. (In the following equations, the symbols α and β are used for the left and the right camera's parameters $\underline{C}$, while subscripts *l* and *r* are used in order to distinguish between the two cameras' image coordinates.)

a. Route 1. Rewrite equations such as (3.8) for both cameras, into equation (3.12), and make use of the definition of the pseudo-inverse of a rectangular matrix - (3.11) - to determine (x,y,z) from (3.13).

b. Route 2. Reduce equation (3.12) into equation (3.14), and determine (x,y,z) from (3.15).

c. Route 3. Rewrite equation (3.12) into equation (3.16), and determine (x,y,z) from (3.17).

$$\begin{bmatrix} (\alpha_1-\alpha_9U_l) & (\alpha_2-\alpha_{10}U_l) & (\alpha_3-\alpha_{11}U_l) \\ (\alpha_5-\alpha_9V_l) & (\alpha_6-\alpha_{10}V_l) & (\alpha_7-\alpha_{11}V_l) \\ (\beta_1-\beta_9U_r) & (\beta_2-\beta_{10}U_r) & (\beta_3-\beta_{11}U_r) \\ (\beta_5-\beta_9V_r) & (\beta_6-\beta_{10}V_r) & (\beta_7-\beta_{11}V_r) \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} U_l-\alpha_4 \\ V_l-\alpha_8 \\ U_r-\beta_4 \\ V_r-\beta_8 \end{bmatrix} \qquad (3.12)$$

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} (\alpha_1-\alpha_9U_l) & (\alpha_2-\alpha_{10}U_l) & (\alpha_3-\alpha_{11}U_l) \\ (\alpha_5-\alpha_9V_l) & (\alpha_6-\alpha_{10}V_l) & (\alpha_7-\alpha_{11}V_l) \\ (\beta_1-\beta_9U_r) & (\beta_2-\beta_{10}U_r) & (\beta_3-\beta_{11}U_r) \\ (\beta_5-\beta_9V_r) & (\beta_6-\beta_{10}V_r) & (\beta_7-\beta_{11}V_r) \end{bmatrix}^{*} \begin{bmatrix} U_l-\alpha_4 \\ V_l-\alpha_8 \\ U_r-\beta_4 \\ V_r-\beta_8 \end{bmatrix} \qquad (3.13)$$

$$\begin{bmatrix} (\alpha_1-\alpha_9U_l) & (\alpha_2-\alpha_{10}U_l) & (\alpha_3-\alpha_{11}U_l) \\ (\alpha_5-\alpha_9V_l) & (\alpha_6-\alpha_{10}V_l) & (\alpha_7-\alpha_{11}V_l) \\ (\beta_1-\beta_9U_r) & (\beta_2-\beta_{10}U_r) & (\beta_3-\beta_{11}U_r) \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} U_l-\alpha_4 \\ V_l-\alpha_8 \\ U_r-\beta_4 \end{bmatrix} \qquad (3.14)$$

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} (\alpha_1-\alpha_9 U_l) & (\alpha_2-\alpha_{10} U_l) & (\alpha_3-\alpha_{11} U_l) \\ (\alpha_5-\alpha_9 V_l) & (\alpha_6-\alpha_{10} V_l) & (\alpha_7-\alpha_{11} V_l) \\ (\beta_1-\beta_9 U_r) & (\beta_2-\beta_{10} U_r) & (\beta_3-\beta_{11} U_r) \end{bmatrix}^{-1} \begin{bmatrix} U_l-\alpha_4 \\ V_l-\alpha_8 \\ U_r-\beta_4 \end{bmatrix} \tag{3.15}$$

$$\begin{bmatrix} (\alpha_1-\alpha_9 U_l) & (\alpha_2-\alpha_{10} U_l) & (\alpha_3-\alpha_{11} U_l) & \alpha_4 \\ (\alpha_5-\alpha_9 V_l) & (\alpha_6-\alpha_{10} V_l) & (\alpha_7-\alpha_{11} V_l) & \alpha_8 \\ (\beta_1-\beta_9 U_r) & (\beta_2-\beta_{10} U_r) & (\beta_3-\beta_{11} U_r) & \beta_4 \\ (\beta_5-\beta_9 V_r) & (\beta_6-\beta_{10} V_r) & (\beta_7-\beta_{11} V_r) & \beta_8 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} U_l \\ V_l \\ U_r \\ V_r \end{bmatrix} \tag{3.16}$$

$$\begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} (\alpha_1-\alpha_9 U_l) & (\alpha_2-\alpha_{10} U_l) & (\alpha_3-\alpha_{11} U_l) & \alpha_4 \\ (\alpha_5-\alpha_9 V_l) & (\alpha_6-\alpha_{10} V_l) & (\alpha_7-\alpha_{11} V_l) & \alpha_8 \\ (\beta_1-\beta_9 U_r) & (\beta_2-\beta_{10} U_r) & (\beta_3-\beta_{11} U_r) & \beta_4 \\ (\beta_5-\beta_9 V_r) & (\beta_6-\beta_{10} V_r) & (\beta_7-\beta_{11} V_r) & \beta_8 \end{bmatrix}^{-1} \begin{bmatrix} U_l \\ V_l \\ U_r \\ V_r \end{bmatrix} \tag{3.17}$$

3.4.3.2.3 Experimental determination of camera models in a stereo vision set-up

In order to experiment with three-dimensional scene description, twelve sharp pointed vertical sticks were mounted onto a plank (refer to Figure 3.3). The three-dimensional coordinates of the endpoint of each vertical stick were accurately determined (measured in [mm] from the one corner of the plank). Two television cameras (about 300 mm apart, and about 2 m from the plank) were used to make video recordings of these sticks; and the corresponding image coordinates were determined for each of the twelve stick endpoints - measured in terms of pixels on the video images of the sticks. (The image coordinates were determined by making use of a movable cursor on the graphics screen - part of the program IMPROC.PAS, of which a summary is included in Appendix E.)

The frames of reference chosen for this experimental set-up, were:

a. World coordinates. The reference point was chosen at one corner of the plank; while the axes were defined as follows, relative to the cameras:

   i. x-axis: horizontal and forward;

   ii. y-axis: horizontal and to the right; and

   iii. z-axis: vertical and downwards.

b. Image coordinates. The reference point was chosen as the upper left corner of the computer monitor on which the image was displayed. The U-axis was chosen to the right; while the V-axis was chosen downwards.

Table 3.6 shows the world coordinates, and the corresponding image coordinates as derived from the two cameras - with subscripts *l* and *r* designating the left and the right camera respectively. (The z-values are negative because the positive z-axis was defined downwards, while the sticks point upwards.)

The odd numbered measurement points in Table 3.6 (hereafter referred to as the *calibration coordinates*) were used to determine the camera parameters ($C_{1,2,...,11}$ in matrix $\underline{C}$) from (3.10); while the even numbered measurement points in Table 3.6 (hereafter referred to as the *verification coordinates*) were used to test the camera models.

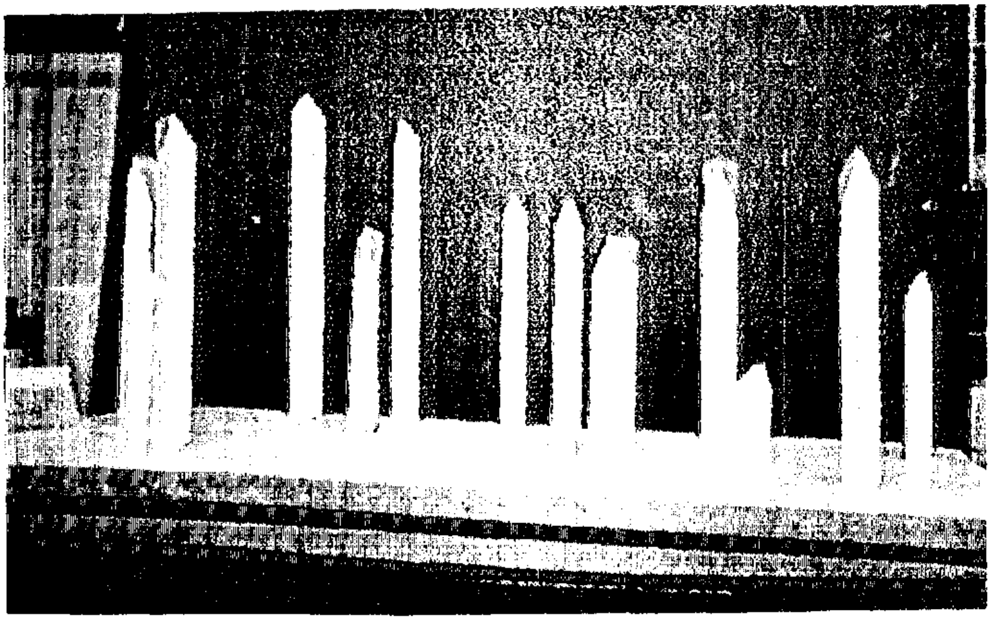


FIGURE 3.3: Twelve vertical sticks mounted on a plank, for scene description experiments

Measurement point number	Measured world coordinates [mm]			Measured image coordinates (left camera) [pixels]		Measured image coordinates (right camera) [pixels]	
	x	y	z	U_l	V_l	U_r	V_r
1	247	69	-175	121	66	121	58
2	96	151	-191	165	53	152	46
3	430	156	-234	158	22	175	16
4	293	235	-136	211	91	206	85
5	125	302	-194	251	49	233	42
6	378	340	-163	252	70	260	63
7	205	403	-154	297	78	289	71
8	46	445	-131	339	99	312	93
9	400	500	-197	318	46	335	37
10	246	533	-60	350	136	364	145
11	100	600	-185	409	52	394	45
12	329	654	-121	388	93	420	92

TABLE 3.6: World- and stereo image coordinates of the twelve sticks shown in Figure 3.3

The two camera models, as shown in equations (3.18) and (3.19), were determined from (3.10) and (3.11), by means of the PC-MATLAB program CAL6.M (refer to Appendix E):

a. Left camera

$$\begin{aligned} \alpha_1 &= 1,2481.10^{-1} \\ \alpha_2 &= 6,1501.10^{-1} \\ \alpha_3 &= 3,0841.10^{-1} \\ \alpha_4 &= 1,0908.10^{2} \\ \alpha_5 &= 4,5637.10^{-2} \\ \alpha_6 &= 1,8181.10^{-3} \\ \alpha_7 &= 8,9405.10^{-1} \\ \alpha_8 &= 2,1542.10^{2} \\ \alpha_9 &= 8,4021.10^{-4} \\ \alpha_{10} &= 2,4893.10^{-4} \\ \alpha_{11} &= 9,3766.10^{-4} \\ \alpha_{12} &= 1,0000 \end{aligned} \qquad (3.18)$$

b. Right camera

$$\begin{aligned} \beta_1 &= 1,5694.10^{-1} \\ \beta_2 &= 5,9486.10^{-1} \\ \beta_3 &= -1,0882.10^{-1} \\ \beta_4 &= 4,8600.10^{1} \\ \beta_5 &= 1,8542.10^{-2} \\ \beta_6 &= -1,6505.10^{-2} \\ \beta_7 &= 8,6937.10^{-1} \\ \beta_8 &= 2,1952.10^{2} \\ \beta_9 &= 5,0628.10^{-4} \\ \beta_{10} &= -5,5604.10^{-5} \\ \beta_{11} &= -5,5614.10^{-4} \\ \beta_{12} &= 1,0000 \end{aligned} \qquad (3.19)$$

3.4.3.2.4 Verification of the camera models

Three steps were taken in order to verify the camera models derived by means of the PC-MATLAB program CAL6.M; and the details of these steps are described in the rest of this section.

3.4.3.2.4.1 Comparing the measured calibration image coordinates with calculated image coordinates

Once the parameters of the left camera and the right camera were determined by means of the program CAL6.M, the process was reversed, in the same program. The (x,y,z) calibration values were used together with the camera models, in order to calculate image coordinates. Theoretically these calculated image coordinates should be identical to the original calibration values of (U_l,V_l) and (U_r,V_r). Slight differences do occur however - due to numerical inaccuracies.

The differences between the calculated values and the original calibration image coordinates, are shown in Table 3.7. It is evident that all the differences have values very close to zero. If the differences were rounded in order to give it in terms of pixel errors, all the errors but two, would be zero. These results clearly indicate the validity of the camera models.

Measure-ment point number	Left camera						Right camera					
	Measured image coordinates		Calculated image coordinates		Calculation error		Measured image coordinates		Calculated image coordinates		Calculation error	
	U_l	V_l	U_l'	V_l'	U_l'-U_l	V_l'-V_l	U_r	V_r	U_r'	V_r'	U_r'-U_r	V_r'-V_r
1	121	66	121,03	66,34	0,03	0,34	121	58	121,01	58,12	0,01	0,12
3	158	22	157,97	22,13	-0,03	0,13	175	16	174,99	16,05	-0,01	0,05
5	251	49	251,01	48,32	0,01	-0,68	233	42	233,00	41,75	0,00	-0,25
7	297	78	296,96	77,85	-0,04	-0,15	289	71	288,99	70,94	-0,01	-0,06
9	318	46	318,03	45,82	0,03	-0,18	335	37	335,01	36,93	0,01	-0,07
11	409	52	409,08	52,53	0,08	0,53	394	45	394,00	45,21	0,00	0,21

TABLE 3.7: Measured calibration image coordinates; and image coordinates calculated from the camera models and the calibration world coordinates

3.4.3.2.4.2 Comparing the measured calibration world coordinates with world coordinates calculated from the camera models and the calibration image coordinates

The next step to verify the validity of the camera models, was to use the calibration image coordinates (of both cameras) and the two camera models, to calculate world coordinates. For this step in the evaluation process, the three routes to calculate world coordinates from two camera models and a stereo pair of image coordinates (Section 3.4.3.2.2.3), were implemented in the PC-MATLAB program THREE_D.M (refer to Appendix E). The three possible calculation routes could thus also be evaluated.

The differences between the world coordinates calculated by means of (3.13), (3.15) and (3.17) respectively, and the calibration world coordinates (from Table 3.6) are shown in Table 3.8. From Table 3.8 it can be seen that the errors in the world coordinates of the calibration points (as calculated by means of Calculation Route 1), have absolute values smaller than 0,8 mm - indicating the accuracy of the derived camera models and of Calculation Route 1. (These errors are due to numerical inaccuracies.) The errors in the world coordinates calculated by means of Route 2 are slightly larger (< 1,2 mm); while the errors in the world coordinates calculated by means of Route 3 are much larger.

It is qualitatively expected that Routes 1 and 3 should produce better results than Route 2, because the latter uses only 3 of the available 4 image coordinates for calculation of the world coordinates of a point. The reason for the poor performance of Route 3 is attributed to the large condition number of the matrix that is inverted in equation (3.17). (For the specific camera parameters in (3.18) and (3.19), and the values in Table 3.6, the values in the last column of this matrix is up to 10^5 times that of those in the first three columns.) Based on the results obtained, it is decided that only Route 1 shall further be used.

3.4.3.2.4.3 Making use of verification points to evaluate the camera models

By making use of the camera models derived by means of the program CAL6.M, and the **verification points** in Table 3.6, the program THREE_D.M was used to calculate a set of world coordinates (x_c,y_c,z_c) by means of equation (3.13) - i.e. Calculation Route 1. Table 3.9 shows the measured world coordinates (x_m,y_m,z_m); the calculated world coordinates (x_c,y_c,z_c); and the differences $(x_e,y_e,z_e) = (x_c,y_c,z_c) - (x_m,y_m,z_m)$.

Measurement point number	Measured world coordinates [mm] (calibration points)			Calculated world coordinates [mm] ("Route 1")			Calculation error [mm] ("Route 1")		
	x_m	y_m	z_m	x_c	y_c	z_c	x_c-x_m	y_c-y_m	z_c-z_m
1	247	69	-175	246,35	69,07	-175,30	-0,65	0,07	-0,30
3	430	156	-234	429,22	156,09	-234,11	-0,78	0,09	-0,11
5	125	302	-194	125,47	301,97	-193,45	0,47	-0,03	0,55
7	205	403	-154	204,69	403,01	-153,87	-0,31	0,01	0,13
9	400	500	-197	400,18	499,97	-196,82	0,18	-0,03	0,18
11	100	600	-185	100,37	600,10	-185,45	0,37	0,10	-0,45

TABLE 3.8a: Differences between calculated world coordinates (Calculation Route 1 and calibration image coordinates), and the measured calibration world coordinates

Measurement point number	Measured world coordinates [mm] (calibration points)			Calculated world coordinates [mm] ("Route 2")			Calculation error [mm] ("Route 2")		
	x_m	y_m	z_m	x_c	y_c	z_c	x_c-x_m	y_c-y_m	z_c-z_m
1	247	69	-175	245,87	69,14	-175,45	-1,13	0,14	-0,45
3	430	156	-234	429,32	156,09	-234,15	-0,68	0,09	-0,15
5	125	302	-194	125,39	301,94	-193,20	0,39	-0,06	0,80
7	205	403	-154	204,71	403,01	-153,80	-0,29	0,01	0,20
9	400	500	-197	400,09	499,95	-196,73	0,09	-0,05	0,27
11	100	600	-185	100,63	600,16	-185,67	0,63	0,16	-0,67

TABLE 3.8b: Differences between calculated world coordinates (Calculation Route 2 and calibration image coordinates), and the measured calibration world coordinates

Measurement point number	Measured world coordinates [mm] (calibration points)			Calculated world coordinates [mm] ("Route 3")			Calculation error [mm] ("Route 3")		
	x_m	y_m	z_m	x_c	y_c	z_c	x_c-x_m	y_c-y_m	z_c-z_m
1	247	69	-175	245,74	70,85	-170,97	-1,26	1,85	4,03
3	430	156	-234	283,00	220,30	-91,38	-147,00	64,30	142,62
5	125	302	-194	143,46	297,72	-204,29	18,46	-4,28	-10,29
7	205	403	-154	208,26	402,55	-155,51	3,26	-0,45	-1,51
9	400	500	-197	408,62	499,49	-200,29	8,62	-0,51	-3,29
11	100	600	-185	82,45	599,90	-178,00	-17,55	-0,10	7,00

TABLE 3.8c: Differences between calculated world coordinates (Calculation Route 3 and calibration image coordinates), and the measured calibration world coordinates

3.4.3.2.5 Errors in the three-dimensional scene description process

The results presented in Section 3.4.3.2.4 above indicate that the error probability along the depth axis during three-dimensional scene description is larger than that along the other two axes. From the simple image formation process described by Figure 3.2 and by equation (3.4), it is obvious that an error in the measured U image coordinate will have an influence on both the calculated x and y world coordinates; while an error in the measured V image coordinate will have an influence on both the calculated x and z world coordinates. This is also true for the generalized image formation process described by equation (3.6b) and (3.6c). The calculated x coordinate of a point is thus influenced by errors along both image coordinates, of both cameras. Furthermore, it is very obvious that errors in the camera models will have an effect on the calculated world coordinates of a point.

In this section, the above two error sources in three-dimensional scene description by means of stereo-vision, are investigated. With stereo-vision, the relative placement of the cameras

Measure -ment point number	Measured world coordinates [mm] (verification points)			Calculated world coordinates [mm] ("Route 1")			Calculation error [mm] ("Route 1")		
	x_m	y_m	z_m	x_c	y_c	z_c	x_c-x_m	y_c-y_m	z_c-z_m
2	96	151	-191	97,28	150,84	-190,76	1,28	-0,16	0,24
4	293	235	-136	294,39	235,38	-136,17	1,39	0,38	-0,17
6	378	340	-163	384,45	340,54	-162,73	6,45	0,54	0,27
8	46	445	-131	43,59	444,12	-130,58	-2,41	-0,88	0,42
10	246	533	-60	244,83	532,69	-59,52	-1,17	-0,31	0,48
12	329	654	-121	335,61	655,36	-120,50	6,61	1,36	0,50

TABLE 3.9: Measured- and calculated world coordinates for the six verification points, with the resulting calculation errors ("Calculation Route 1")

also have an influence on the accuracy of scene description. This aspect is also briefly addressed in this section.

3.4.3.2.5.1 Sensitivity of calculated world coordinates for relative placement of cameras

From the experimental work it was found that the three-dimensional scene description process is sensitive for changes in the relative positions of the two cameras in a stereo-vision set-up. To illustrate this, consider the following simplified three-dimensional scene description process:

The centre points of the imaging planes of two cameras are a horizontal distance k apart. The imaging plane of camera #1 is parallel with a plane on which a world point (x,y,z) is situated. The line from the world point intersects the imaging plane of camera #1 at its centre, and is at a right angle with the imaging plane. The line from the world point also intersects the imaging plane of camera #2 at its centre. The angle between these two lines (measured at the two lines' intersection at the world point) is θ. The distance from camera #1 to the world point is $x = k / \tan \theta$; which simplifies to $x = k/\theta$, for small θ. The value of k is related to, and can be determined from the values of the image coordinates in the two images. Assume $\theta = 0,1$ rad, then a small error in k (i.e. in the measured image coordinates of one of the images), will result in 10 times that error in x.

From the above simplified description it is evident that the two cameras should not be too close together (i.e. θ must not be too small). On the other hand, if they are too far apart, stereo correlation (refer to Section 3.4.5 below) can become a problem.

It seems that there should be an optimum value for displacement of the two cameras in a stereo-vision set-up. Since the experimental results obtained were satisfactory for the purposes of this project, and since a full investigation into this subject can be an extensive exercise, this issue will not be investigated further here. (It is instead included in the list of *suggestions for further research*, presented in Chapter 5.)

3.4.3.2.5.2 Sensitivity of calculated world coordinates for errors in measured image coordinates

In order to practically investigate the influence of errors in the measured image coordinates, on the accuracy of world coordinates calculated by means of the camera models in (3.18) and (3.19), the following extensions were made to the program THREE_D.M (refer to Appendix E):

a. Fixed errors (positive or negative) can be specified by the program user, to be added in both images, to the measured U-coordinates, or to the measured V-coordinates, or to both. (The images are thus shifted along the U-, or the V-, or along both image axes, by a certain number of pixels).

b. Random errors (positive and negative - within bounds specified by the program user) are added individually to each of the image coordinates - in a similar fashion as that described in (a) above. (Because of the random nature of the errors added to the image coordinates in this case, the results thus obtained will differ each time the program is executed.)

Table 3.10a shows the errors in the calculated world coordinates, caused by a fixed bias of +10 pixels added to each of the U-coordinates (horizontal) of the verification image points (as indicated in Table 3.6) derived by means of both cameras. Table 3.10b shows the errors in the calculated world coordinates, caused by a fixed bias of +10 pixels added to each of the V-coordinates (vertical) of the verification image points derived from both cameras.

This sensitivity analysis was concluded by means of a Monte-Carlo type analysis - performed by the PC-MATLAB program MONTE.M (Appendix E). First random errors of between -2% and +2% of the image coordinate values, and then random errors of between -10% and +10% of the image coordinate values were added to each verification image coordinate - for both images. From the two camera models, and these "corrupted" verification image coordinates, the world coordinates were determined (with Route 1). In each of the two cases, the process was repeated 100 times, and the average values and the standard deviations determined for the calculated x-, y-, and z-coordinates. Table 3.11 shows the measured world coordinates of each verification point (from Table 3.6); the average (μ) and the standard deviation (σ) of the 100 calculated values; as well as the calculation errors.

Measurement point number	Measured world coordinates [mm] (verification points)			Calculated world coordinates [mm] ("Route 1")			Calculation error [mm]		
	x_m	y_m	z_m	x_c	y_c	z_c	x_e	y_e	z_e
2	96	151	-191	113,25	167,85	-190,48	17,25	16,85	0,52
4	293	235	-136	288,66	255,78	-135,98	-4,34	20,78	0,02
6	378	340	-163	374,47	361,62	-162,54	-3,53	21,62	0,46
8	46	445	-131	37,19	461,50	-130,48	-8,81	-16,50	0,52
10	246	533	-60	224,36	550,11	-60,57	-21,64	17,11	-0,57
12	329	654	-121	315,18	672,83	-120,89	-13,82	18,83	0,11

TABLE 3.10a: <u>Differences between calculated and measured world coordinates (verification image coordinates of both cameras shifted with +10 pixels along U-axis)</u>

Measurement point number	Measured world coordinates [mm] (verification points)			Calculated world coordinates [mm] ("Route 1")			Calculation error [mm]		
	x_m	y_m	z_m	x_c	y_c	z_c	x_e	y_e	z_e
2	96	151	-191	120,83	148,17	-178,52	24,83	-2,83	12,48
4	293	235	-136	307,43	233,95	-121,87	14,43	-1,05	14,13
6	378	340	-163	389,36	339,44	-148,09	11,36	-0,56	14,91
8	46	445	-131	37,98	442,75	-118,72	-8,02	-2,25	12,28
10	246	533	-60	230,67	529,41	-46,88	-15,33	-3,59	13,12
12	329	654	-121	319,77	650,92	-106,68	-9,23	-3,08	14,32

TABLE 3.10b: Differences between calculated and measured world coordinates (verification image coordinates of both cameras shifted with +10 pixels along V-axis)

Measurement point	Measured world coordinates [mm] (verification points)			Calculated world coordinates [mm] ("Route 1"); average (μ) and standard deviation (σ) - as calculated from 100 Monte-Carlo runs						Calculation error [mm] (average calculated values (μ) minus measured values)		
	x_m	y_m	z_m	x_c		y_c		z_c		x_e	y_e	z_e
				μ_x	σ_x	μ_y	σ_y	μ_z	σ_z			
2	96	151	-191	97,28	32,43	150,75	2,71	-190,71	0,49	1,28	-0,25	0,29
4	293	235	-136	294,23	44,64	235,24	3,13	-136,07	1,77	1,23	0,24	-0,07
6	378	340	-163	384,65	51,54	340,37	4,65	-162,64	1,16	6,65	0,37	0,36
8	46	445	-131	43,49	35,99	443,91	6,02	-130,48	1,75	-2,51	-1,09	0,52
10	246	533	-60	244,40	47,01	532,36	8,50	-59,39	3,84	-1,60	-0,64	0,61
12	329	654	-121	335,81	53,72	655,10	12,63	-120,37	2,36	6,81	1,10	0,63

TABLE 3.11a: Measured world coordinates (verification points), and world coordinates calculated from 100 Monte-Carlo runs (-2% ≤ ϵ ≤ +2% random errors added to both cameras' U- and V-verification image coordinates)

Measurement point	Measured world coordinates [mm] (verification points)			Calculated world coordinates [mm] ("Route 1"); average (μ) and standard deviation (σ) - as calculated from 100 Monte-Carlo runs						Calculation error [mm] (average calculated values (μ) minus measured values)		
	x_m	y_m	z_m	x_c		y_c		z_c		x_e	y_e	z_e
				μ_x	σ_x	μ_y	σ_y	μ_z	σ_z			
2	96	151	-191	86,04	141,29	151,82	13,59	-190,79	2,51	-9,96	0,82	0,21
4	293	235	-136	279,98	191,43	235,88	17,98	-136,67	8,40	-13,02	0,88	-0,67
6	378	340	-163	372,96	223,12	340,49	25,95	-162,95	5,76	-5,04	0,49	0,05
8	46	445	-131	33,03	154,33	443,11	30,98	-131,04	8,23	-12,97	-1,89	-0,04
10	246	533	-60	231,32	199,98	530,90	41,47	-60,59	9,81	-14,68	-2,10	-0,59
12	329	654	-121	325,57	232,01	653,61	60,15	-120,93	9,00	-3,43	-0,39	0,07

TABLE 3.11b: Measured world coordinates (verification points), and world coordinates calculated from 100 Monte-Carlo runs (-10% ≤ ϵ ≤ +10% random errors added to both cameras' U- and V-verification image coordinates)

On comparing the results in Tables 3.10 and 3.11, with that in Table 3.9, the following conclusions are reached (for the specific stereo vision set-up used to derive the data in Table 3.6):

a. With errors of 10 pixels added along the U (horizontal) axis of the two images, errors of up to 22 mm in the calculated x world coordinates; errors of up to 22 mm in the calculated y world coordinates; and errors less than 1 mm in the calculated z world coordinates occur.

b. With errors of 10 pixels added along the V (vertical) axis of the two images, errors of up to 25 mm in the calculated x world coordinates; errors of up to 4 mm in the calculated y world coordinates; and errors of up to 15 mm in the calculated z world coordinates occur.

c. With random errors of between -2% and +2% added along both the U and the V axes of the two images, the average values of the calculated x-, y-, and z world coordinates are similar to the values shown in Table 3.9. The standard deviations are large however (and that of the calculated x coordinates are typically an order of magnitude larger than that of the calculated y and z coordinates), indicating that some calculated values differ largely from the measured values.

d. With random errors of between -10% and +10% added along both the U and the V axes of the two images, the average values of the calculated x-, y-, and z world coordinates are also similar to the values shown in Table 3.9. With the error bounds increased by 5 times (from 2% to 10%), the average values remained in the same order, but the standard deviations are also about 5 times larger.

e. Overall, it is evident that the depth axis of a three-dimensional scene description system is the most sensitive to errors in the measured image coordinates. In order to ensure accurate object localisation by means of three-dimensional scene description, it is essential to measure the image coordinates in the stereo images very accurately.

3.4.3.2.5.3 Sensitivity of calculated world coordinates for errors in camera models

The accuracy of the camera parameters in (3.18) and (3.19) was evaluated in Section 3.4.3.2.4 above; and the results obtained indicated the validity of the camera model, and of the parameters. In this section the sensitivity of calculated world coordinates for errors in the camera calibration process (i.e. errors in camera parameters) is investigated, in order to emphasise the importance of accurate camera calibration.

Measurement point	Measured world coordinates [mm] (verification points)			Calculated world coordinates [mm] ("Route 1"); average (μ) and standard deviation (σ) - as calculated from 100 Monte-Carlo runs						Calculation error [mm] (average calculated values (μ) minus measured values)		
	x_m	y_m	z_m	x_c		y_c		z_c		x_e	y_e	z_e
				μ_x	σ_x	μ_y	σ_y	μ_z	σ_z			
2	96	151	-191	92,34	73,71	150,54	6,84	-190,96	1,16	-3,66	-0,46	0,04
4	293	235	-136	288,24	92,58	234,65	6,67	-136,69	3,56	-4,76	-0,35	-0,69
6	378	340	-163	378,00	97,88	339,23	9,60	-163,09	2,19	0,00	-0,77	-0,09
8	46	445	-131	38,99	84,48	442,26	14,49	-131,12	3,95	-7,01	-2,74	-0,12
10	246	533	-60	239,10	98,07	530,36	19,43	-60,44	8,15	-6,90	-2,64	-0,44
12	329	654	-121	329,52	101,92	652,38	25,99	-121,09	4,52	0,52	-1,62	-0,09

TABLE 3.12: Measured world coordinates (verification points), and world coordinates calculated from 100 Monte-Carlo runs ($-5\% \leq \epsilon \leq +5\%$ random errors added to both cameras' parameters)

Table 3.12 shows the calculation errors obtained from a Monte-Carlo type analysis, if each camera parameter (for both camera models) is corrupted by a random error between -5% and +5% of the true value of the camera parameter. (The average and the standard deviation were determined after the calculation process was repeated 100 times.) Although the average values of the calculated x-, y-, and z world coordinates are similar to the values shown in Table 3.9, the standard deviations are large, indicating that some calculated values differ largely from the measured values. From this results it is again evident that the largest sensitivity is experienced along the depth (x-) axis. These results also make it very clear that accurate camera calibration is essential for successful three-dimensional scene description.

3.4.3.2.6 Conclusions on the feasibility of three-dimensional scene description for the milking robot

From Table 3.9 it is evident that errors in the horizontal plane of less than 7 mm could be attained (with the specific experimental machine perception set-up described in Appendix A), when using two calibrated cameras, and the image coordinates in two stereo images, to calculate the world coordinates of objects. These errors are smaller than the specified 9 mm for the milking robot's machine perception subsystem (refer to Section 3.4.2). (Although accurate measurement of the image- and the world coordinates for the calibration and the verification points are aspects which require special attention, the results shown in Table 3.9 were obtained without extreme care being taken in this regard.)

For the milking robot, inaccurate three-dimensional scene description - especially along the depth axis - is a problem. It can nevertheless be concluded that the principle of three-dimensional scene description, by making use of the camera model as defined in equation (3.10), is a feasible concept for implementation as part of a milking robot.

However, before a cow's teats can be localised in terms of world coordinates, they must first be localised accurately in the two images of the udder (i.e. in terms of image coordinates). In the experiments described above, the image coordinates were determined manually, by means of a movable cursor on the graphics screen. This process must however be automated - giving rise to a very important question: *How are the image coordinates of specific pre-defined features found in an image ?* Different techniques exist for this purpose, and the most important ones are discussed in Section 3.4.4.

A second very important question deals with how to ascertain that the same object is located in both images. The so-called stereo correlation problem is very relevant in the milking robot context, and it is addressed in Section 3.4.5.

3.4.4 FINDING SCENE FEATURES IN IMAGES

In this section, the most important characteristics of a number of techniques for finding scene features in images, are discussed qualitatively. Based on this discussion, one of the concepts is investigated in detail - both theoretically and by means of suitable experiments.

3.4.4.1 <u>TEMPLATE MATCHING</u>

Template matching is one of the most elementary forms of locating pre-defined features in an image. The images (templates) of pre-defined objects are compared with the image in which certain features must be located. This is done by comparing individual pixels of the template, with all the pixels of the image. (Refer to HALL (1979, p.480); and DUDA & HART (1973, p.276).) The main disadvantage of this technique - restricting its suitability for use as part of a milking robot's machine perception system - is: Unless the template is a good representation (in shape, size, and orientation) of the object searched for, correlation between the template and the object is difficult. Different templates can be compared pixel by pixel with the image, but this method is very computer intensive.

3.4.4.2 <u>CONTOUR FOLLOWING IN A BINARY IMAGE</u>

Different algorithms exist for tracing contours in images. An algorithm for following the contour of a binary image (where background pixels have the value 0, and non-background pixels have the value 1) is defined by DUDA & HART (1973, p.291) as follows:

Scan the image until pixel value = 1 is found (and mark it as "starting pixel");
Then repeat until reaching the starting pixel again:
If pixel value = 1, then turn left and move on to next pixel;
Else if pixel value = 0, then turn right and move on to next pixel.

(Refer to Figure 3.4 for an illustration of the algorithm. In this picture, all the pixels enclosed by the contour are 1's, while all other pixels are 0's. All pixels have the same colour in the picture however, only in order to clearly indicate the path of the contour follower.)

The above algorithm is suitable for tracing the closed contour of a single object in an image; but it can also be adapted to trace the contours of more than one object in the same image, and to trace the visible contours of objects which go beyond the limits of the display unit.

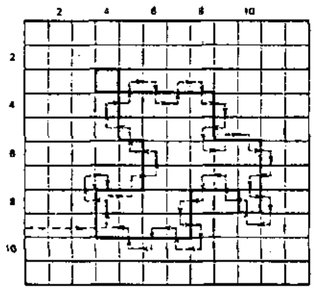


FIGURE 3.4: <u>Contour following in a binary image</u>

For locating the endpoints of a cow's teats, the algorithm must be adapted to record a turning point in the contour - making it a special case of pattern recognition, as discussed in Section 3.4.4.4 below. Although the algorithm seems simple, it is not a trivial task to implement it. During experimentation with this technique, a number of important practical aspects were identified:

a. Because of image noise, a false starting pixel was often found - even in a binary image in which single edge points (noise) were removed by means of an image filter. This resulted in the edge follower moving around this one pixel continuously - thus appearing to stand still at one point.

b. A suitable background colour must be provided to have enough contrast between the udder and teats, and the background - in order to obtain a suitable binary image of the teats. (This can pose a problem when there is much variety in the udder and teat colours of the cows to be milked; but such a problem can be solved by adapting the background colour for individual cows, once the cow has been identified.)

c. Some cows have dark spots on light coloured teats (or *vice versa*), resulting in binary images with discontinuities in the edges, or in the images of the teats. This can cause false points to be marked as teat endpoints.

d. A threshold must be chosen for converting the grey-scale image to a binary image (*procedure binary_image* in the program IMPROC.PAS - refer to Appendix E). Grey-scale histograms are commonly used for determination of binary thresholds, but this process relies on a distinctive colour difference between image and background.

From the above analysis of contour following in a binary image, it is clear that there are many negative aspects, restricting the feasibility of this concept as part of a milking robot.

3.4.4.3 LINE FOLLOWING IN AN EDGE ENHANCED IMAGE

3.4.4.3.1 Edge enhancement

ATTNEAVE (1954) found in experiments with the human visual system, that objects could often be adequately recognised from a rough outline sketch. From this finding it was concluded that the most information about an image is contained in and around the edges of objects in an image. Over many years, a large number of algorithms have been developed for enhancing edges in images, and for discarding the rest of the data. Appendix B contains a discussion of a representative sample of algorithms for this purpose. One class of edge enhancement operators determine possible edges in a digitized image - with image coordinates (i,j) and grey-scale values f(i,j) - by determining the spatial gradients (or intensity changes) in the image. This is done similar to the detection of changes in algebraic functions - i.e. by differentiation.

Appendix B contains results of an analysis performed by CHRISTIANSEN (1990), in order to compare the performance of different edge enhancement algorithms. CHRISTIANSEN (1990) concluded that the **Sobel operator** was the most suitable to be used in images such as the udders of cows. This conclusion correlated with the author's own qualitative analysis - which involved inspection of edge enhanced images obtained by means of different algorithms. (ELSTER & GOODRUM (1991) have also evaluated several edge enhancement algorithms, as part of research on an automated egg sorter. Their conclusion was: "*The use of a Sobel convolution operator enhanced the image better than other methods investigated [...].*")

The Sobel edge enhancement operator determines the magnitude of the intensity gradient at a point (i,j) in an image, by means of equation (3.20), and the direction of a possible edge by (3.21):

$$m(i,j) = [S_x^2 + S_y^2]^{1/2} \qquad (3.20)$$

$$\theta(i,j) = \arctan(S_x/S_y) \qquad (3.21)$$

with:-

$$S_x = [f(i+1,j-1) + 2.f(i+1,j) + f(i+1,j+1)] - [f(i-1,j-1) + 2.f(i-1,j) + f(i-1,j+1)] \qquad .....(3.22)$$

$$S_y = [f(i-1,j+1) + 2.f(i,j+1) + f(i+1,j+1)] - [f(i-1,j-1) + 2.f(i,j-1) + f(i+1,j-1)] \qquad .....(3.23)$$

(Refer to Figure B.1 for a depiction of pixel (i,j) - with intensity f - and its eight neighbours.)

3.4.4.3.2 Line following

Similar to contour following in a binary image, line following can also be done in an edge enhanced version of an image. Different algorithms for this purpose are described in the literature - e.g. LAI & SUEN (1981); MÉRŐ (1981); and SHIPMAN et al (1984).

The main problem with this type of edge follower is that it experiences difficulties when it reaches a discontinuity in the edge image; but McKEE & AGGARWAL (1975) have developed an algorithm to overcome this problem. Their algorithm includes edge marking (edge enhancement by means of one of the operators discussed in Appendix B); edge refining (edge thinning - e.g. ARCELLI & DI BAJA (1985), or MATSUMOTO et al (1990)); edge tracing; and edge completion. During experimentation, the algorithm of McKEE & AGGARWAL (1975) was however found very complex to implement; and consequently it is also computationally slow.

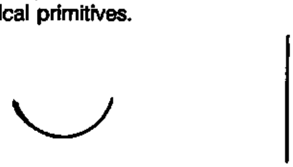
From the above analysis of line following in an edge enhanced image, it is clear that there are also negative aspects, reducing its feasibility as part of a milking robot.

3.4.4.4 PATTERN RECOGNITION

The term pattern recognition is often used as a generic term for the process of *finding scene features in an image*. In this dissertation, the term will however be used in a more specific sense. Pattern recognition corresponds to template matching, in the sense that pre-defined patterns are searched in an image. It differs from template matching however, in the sense that the searched patterns are only defined in broad terms. (The literature under *Pattern Recognition* in Appendix G, contains extensive discussions on this topic.) Pattern recognition for the milking robot was only investigated qualitatively, and not experimentally. The most important principles of the technique are however discussed because similar principles apply to other techniques which were investigated more thoroughly - and which are discussed later in the chapter.

3.4.4.4.1 Syntactic pattern recognition

Syntactic pattern recognition is based on the concepts of structure analysis found in formal language theory. The fundamental aspect of syntactic pattern recognition is the decomposition of patterns into subpatterns or primitives. Figure 3.5 shows a possible decomposition of a cow's teat in terms of typical primitives.



a b

FIGURE 3.5: Typical primitives for syntactic representation of a cow's teat

In order for an image object to be classified as a cow's teat, a number of primitives must be found in the image, and their positions must be related to each other, such that it is described by the syntax *bbbabbb* (as per Figure 3.5). NEL (1987) used this technique for localising a human eye in an investigation of machine enabled communication systems for severely disabled patients. Different patterns could be recognised - such as a fully open eye; an eye with its top half covered by the eye lid; etc. SHELMAN (1970) used a similar technique for the analysis of fingerprints, and for the analysis of chromosomes in microscope images.

3.4.4.4.2 Semantic pattern recognition

Semantic pattern recognition makes use of the "meaning" of the subpatterns in an image. Although primitive a in Figure 3.5 can occur with different orientations in an image of a cow's udder, it can only represent a cow's teat if it points nominally downwards.

3.4.4.5 THE HOUGH TRANSFORM APPLIED TO AN EDGE ENHANCED IMAGE

HOUGH (1962) suggested a technique for locating lines in a digital image (typically an edge enhanced image - refer to Appendix B), by mathematically detecting collinear points. The method involves the transformation from one parameter space (in this case two-dimensional image coordinates) into another parameter space; and is commonly used for detection of straight lines in edge enhanced images. (The basic principles of the method are illustrated by means of several examples in Appendix C.)

From the inspection of numerous edge enhanced images of cows' teats, it was concluded that such images resembled parabolas; and that it should be possible to use the Hough transform to localise these parabolas in images of cows' udders. In order to test this hypothesis, the parabolic Hough transform was applied to edge enhanced images of cows' teats. Although it is a rather intricate problem to detect parabolas by means of the Hough transform (refer to Appendix C), the method holds a number of important advantages, including:

a. If there are distinctive parabolas in an edge enhanced image, the Hough transform will detect such parabolas irrespective of the distances between the individual pixels on the parabola. This feature makes the Hough transform insensitive for gaps in edge enhanced curves in images. (Sensitivity for edge gaps is a problem with most other methods for finding scene features in edge enhanced images - unless the complex process of edge completion (e.g. McKEE & AGGARWAL (1975)) is performed.)

b. For the same reason, the Hough transform is not very sensitive for image noise and discretisation noise in an edge enhanced image.

c. The Hough transform can detect numerous curves (even overlapping) in the same image (as illustrated in Section C.2, where two crossing lines are detected); and a specified curve in the presence of another type of curve (as illustrated in Section C.4, where a parabola is detected in an image with a line crossing the parabola.)

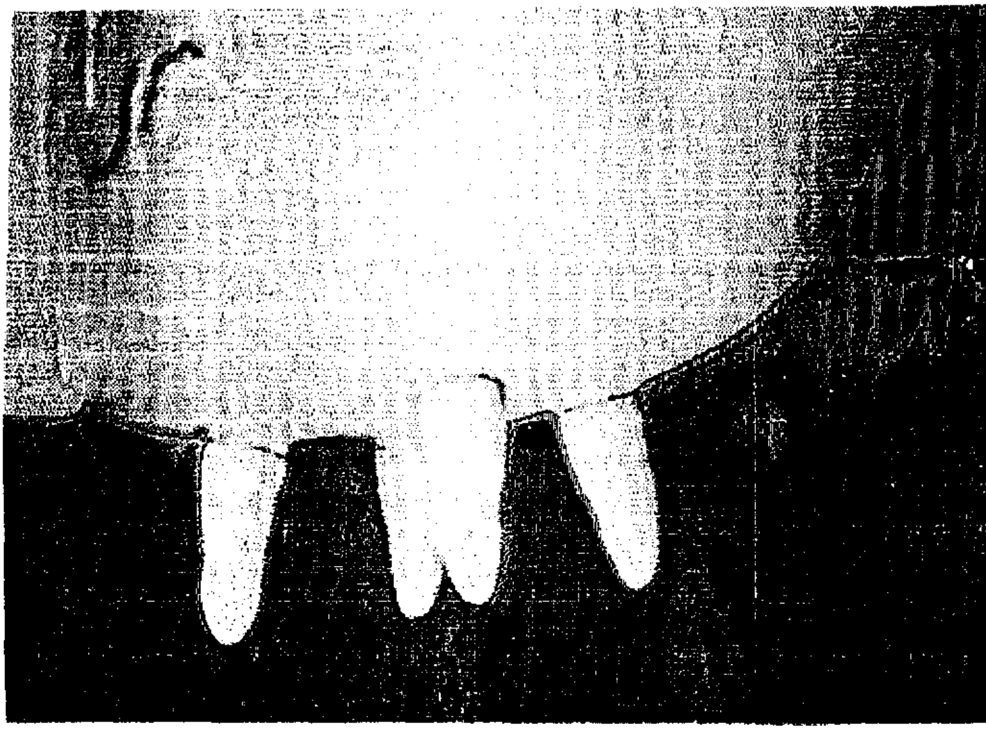


FIGURE 3.6a: Grey-scale image of an artificial cow's udder

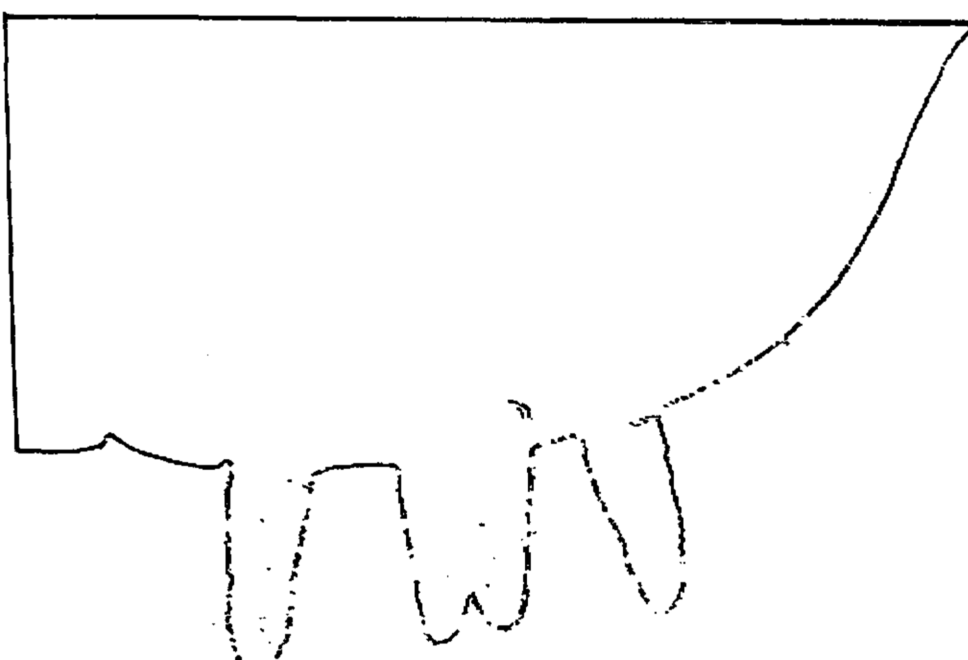


FIGURE 3.6b: Edge enhanced image of an artificial cow's udder

The main disadvantage of the Hough transform, is its computer intensiveness. In the current experimental set-up (see Appendix A), this is a serious drawback. Since the technique is very suitable for parallel processing, due to the repetitive nature of the calculations, it will however be possible to solve the problem by means of appropriate computer hardware.

3.4.4.5.1 First experimental results with the Hough transform applied to the image of an artificial cow's udder

After some preliminary work regarding the Hough transform, and the successful localisation of different rotated parabolas in images (refer to Section C.4), the method was tried on the image of an artificial cow's udder. A grey-scale image and an edge image of this udder are shown in Figure 3.6a and 3.6b respectively.

From Figure 3.6 it can be seen that parts of the left rear and the right front teats are occluded by each other. With the aid of a movable cursor on an image displayed on the computer screen (refer to Appendix A), a number of image coordinates were determined for each teat shown in Figure 3.6. These image coordinates are contained in Table 3.13. (V is measured downwards from the screen's top left corner; and U is measured from the same point to the right.)

Measured image coordinates of an artificial cow's teats [pixels]							
Left rear teat		Left front teat		Right rear teat		Right front teat	
U_{lr}	V_{lr}	U_{lf}	V_{lf}	U_{rr}	V_{rr}	U_{rf}	V_{rf}
243	210	167	129	335	94	270	151
236	230	160	169	340	124	269	191
228	237	154	209	345	164	266	216
222	230	151	239	345	184	259	225
219	219	145	249	342	214	249	220
216	199	137	255	339	218	243	210
212	169	128	245	335	222		
		125	235	330	217		
		125	205	326	212		
		125	165	312	174		
		125	135	306	151		
				298	111		

TABLE 3.13: <u>Image coordinates of edge points in the image of an artificial cow's udder (as shown in Figure 3.6b)</u>

	Measured image coordinates of artificial cow's teat endpoints [pixels]		Image coordinates of artificial cow's teat endpoints - calculated by means of Hough transform [pixels]		Calculation error [pixels]	
	U_m	V_m	U_c	V_c	U_e	V_e
Left rear	228	237	230	236	2	-1
Left front	137	255	139	255	2	0
Right rear	335	222	332	215	-3	-7
Right front	259	225	257	219	-2	-6

TABLE 3.14: Measured and Hough transform calculated image coordinates of an artificial cow's teat endpoints

Appendix E contains a summary of a PC-MATLAB program HOUART.M, written for detection of parabolas in the image of the artificial udder, by making use of the data in Table 3.13. Figure 3.7 contains the results obtained from this experiment (plotted by means of the program PLOTART.M).

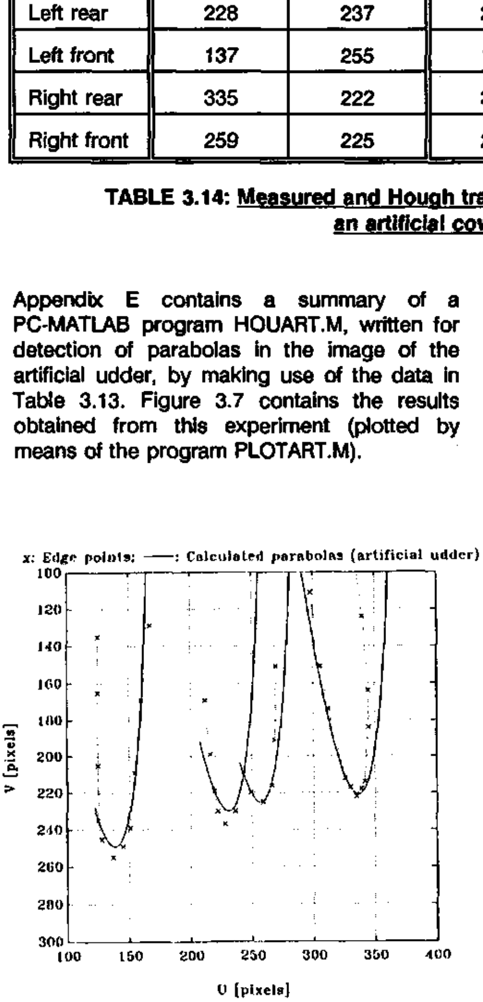


FIGURE 3.7: Manually determined edge pixels on an artificial cow's teats (x) and parabolas fitted to the image (solid lines) by means of the Hough transform

For the milking robot, only the image coordinates of the teat endpoints are of importance. (Refer to the discussions in Section 3.4.2 and in the first paragraph of Section 4.4.) Table 3.14 contains a comparison of the actual measured image coordinates of the endpoints (measured by means of the cursor on the graphics screen), and the image coordinates of the endpoints, as calculated by means of the Hough transform. (The Hough transform calculates the endpoint coordinates directly, since it calculates the x-offset and y-offset of a detected parabola's turning point - which are the desired image coordinates.)

Even though the manually determined edge pixels on an artificial cow's teats do not form perfect parabolas, relatively small localisation errors were obtained experimentally by means of the parabolic Hough transform - as shown in Figure 3.7 and Table 3.14. The calculation errors in image coordinates - as shown in Table 3.14 - are between 0 and 4% of the real image coordinate values. Should these calculated image coordinates thus be used to calculate three-dimensional world coordinates (of course a second image is necessary for this), errors of up to twice those shown in Table 3.11a can be expected in some cases. Although the standard deviations shown in Table 3.11a are large, the average values of the errors are small; and such values are within tolerable limits for a milking robot.

(A teatcup attached to a teat will not influence the parabolic shapes of the other teats. It is therefore obvious that such a teatcup should have no influence on the Hough transform's ability to detect the parabolic shapes of the remaining teats.)

3.4.4.5.2 Three-dimensional localisation of teat endpoints, making use of image coordinates derived from the Hough transform

After using the manually determined image coordinates of the teats on an artificial cow's udder, the next step was to apply the Hough transform to an edge enhanced image of the artificial udder. The following steps were performed for this purpose:

a. The artificial cow's udder was placed between the two cameras and the plank with the sticks mounted on it (Figure 3.3). (The cameras and the plank were in the same configuration than that used for deriving the camera parameters in (3.18) and (3.19) - i.e. the cameras were about 300 mm apart; about 2 m from the plank; and about 1,5 m from the udder.)

b. The world coordinates of the teat endpoints of the artificial cow's udder were measured relative to the reference point on the plank - and recorded in Table 3.15. (The x-coordinates are negative since the reference point was further from the cameras than the udder - i.e. the plank was beyond the udder's position; while the z-coordinates are positive since the reference point was above the udder. This differs from previous cases; but it was chosen as such in order to simultaneously prove that a differently located reference point can be used.)

c. The Hough transform was applied to the edge enhanced images (obtained by means of the Sobel operator - as described in Appendix B) from the left and the right cameras (program HOUART1.M), with the resulting image coordinates of the teat endpoints as shown in Table 3.15. (Figure 3.8 shows the left camera's images.)

d. The program THREE-D.M was used to calculate the three-dimensional world coordinates of the teat endpoints, from the image coordinates derived by means of the Hough transform. The results of these calculations are shown in Table 3.15 - from which it is clear that the parabolic Hough transform is a feasible concept for the localisation of a cow's teat endpoints in an edge enhanced image.

Image coordinates - calculated from Hough transform [pixels]				Calculated world coordinates [mm]			Measured world coordinates [mm]			Calculation error [mm]		
Left camera		Right camera										
U_l	V_l	U_r	V_r	x_c	y_c	z_c	x_m	y_m	z_m	x_c-x_m	y_c-y_m	z_c-z_m
330	386	171	430	-522	265	94	-528	264	91	6	1	3
400	363	270	426	-494	374	96	-493	375	96	-1	-1	0
424	354	305	419	-487	412	93	-484	414	94	-3	-2	-1
489	345	387	417	-504	503	87	-500	507	88	-4	-4	-1

TABLE 3.15: <u>Three-dimensional world coordinates of an artificial cow's udder - as calculated from the stereo image coordinates determined by means of the Hough transform</u>

3.4.4.5.3 Practical problems experienced during the application of the Hough transform to the images of an artificial cow's udder

A number of practical problems were experienced during the application of the Hough transform to the images of an artificial cow's udder. The most serious problem resulted from the "*tricks*" required in order to avoid a multi-dimensional accumulator array when detecting parabolas by means of the Hough transform implemented in PC-MATLAB (refer to Appendix C). Because the accumulator array must be initialised often (due to computer memory limitations), it is currently not possible to detect more than one parabola in the same image. (Note that this is a computer memory problem, and not a problem with the Hough transform - which will definitely be solved in future by the rapid developments in computer abilities.) For experimental purposes, the edge image of the udder was segmented manually, in order to analyze the four teats individually. The results were then combined later, in order to form Figures 3.7 and 3.8(e). Although this problem can be overcome by improved management of the data, and by increased memory, it was not further addressed during this research. This decision was taken since the main focus of this investigation was to illustrate the **feasibility** of the parabolic Hough transform for the milking robot.

In order to detect more than one parabola in the same image, it is not adequate to only use the maximum value of the accumulator array. A threshold is required with which the accumulator contents can be compared. Each accumulator entry which is larger than the threshold, is then considered to represent a possible curve in the picture. WHITTAKER et al (1987) did excellent work on the determination of suitable threshold values for circle detection. This aspect will have to be researched further for the parabolic Hough transform, in order to ensure its successful application in the milking robot context.

3.4.4.5.4 Application of the parabolic Hough transform to the edge enhanced images of real cows' teats

Although it had been concluded that the images of the artificial cow's teats could be approximated by parabolas, an important question remained whether it was true for a real cow's teats as well.

Figure 3.9a shows the grey-scale image of four large brownish teats, somewhat protruding to the sides. A large part of the left rear teat is occluded by the right front teat. Figure 3.9b shows the edge enhanced image of the teats obtained by means of the Sobel operator; and the parabolas calculated by means of the Hough transform.

Figure 3.10a shows the grey-scale image of four small black teats, hanging close together and straight down. Figure 3.10b shows the edge enhanced image of the left rear teat obtained by means of the Sobel operator; and the parabola calculated by means of the Hough transform. (Since the Sobel operator resembles algebraic differentiation, image noise is amplified. The blob in the top part of Figure 3.10b is due to light reflected from the wet teat after it had been washed.) It is noted that the Hough transform performs well, even in such a noisy image.

Figure 3.11a shows the grey-scale image of four medium sized white teats, also somewhat protruding to the sides. Figure 3.11b shows the edge enhanced image of the right front teat obtained by means of the Sobel operator; and the parabola calculated by means of the Hough transform. (The blob on the teat's endpoint is a drop of water hanging on the teat after the udder had been washed.)

From the results shown in Figures 3.9 to 3.11, it can be seen that the parabolic Hough transform performs excellent when applied to the edge enhanced images of real cows' teats. (Although the localising accuracy in terms of image coordinates, cannot be determined very well from Figures 3.9b, 3.10b, and 3.11b, it is clear that the pixel errors are in all three cases less than 10 pixels - which is again within 2-3% from the true image coordinates.)

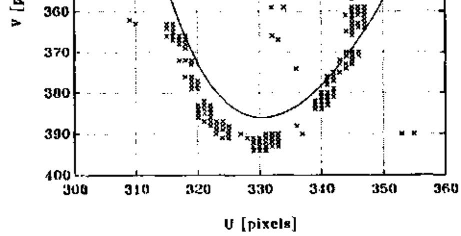


FIGURE 3.8a: Edge pixels (x) on the right rear teat of the udder in Figure 3.6 (determined by means of the Sobel operator) and parabola (solid line) fitted to the image by means of the Hough transform

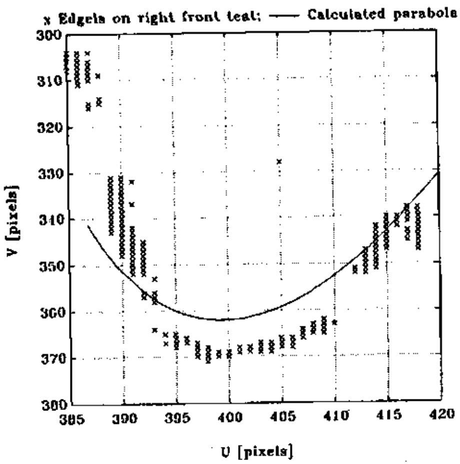


FIGURE 3.8b: Edge pixels (x) on the right front teat of the udder in Figure 3.6 and parabola fitted to the image by means of the Hough transform

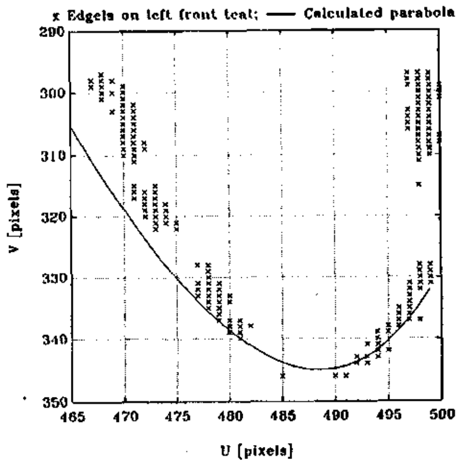


FIGURE 3.8d: Edge pixels (x) on the left front teat of the udder in Figure 3.6 and parabola fitted to the image by means of the Hough transform

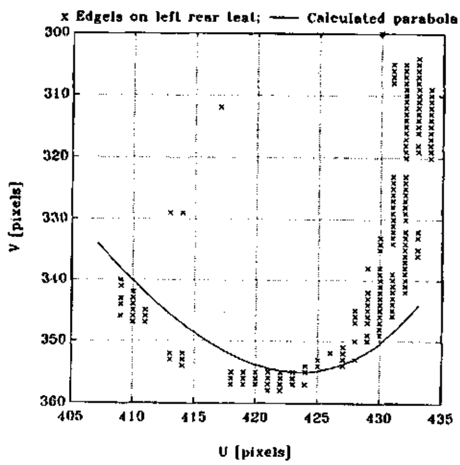


FIGURE 3.8c: Edge pixels (x) on the left rear teat of the udder in Figure 3.6 and parabola fitted to the image by means of the Hough transform

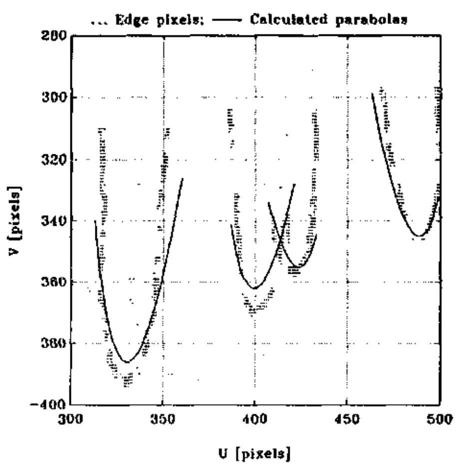


FIGURE 3.8e: Edge pixels (...) of the udder in Figure 3.6 and parabolas (solid lines) fitted to the image by means of the Hough transform

FIGURE 3.9a: Grey-scale image of four large brown teats

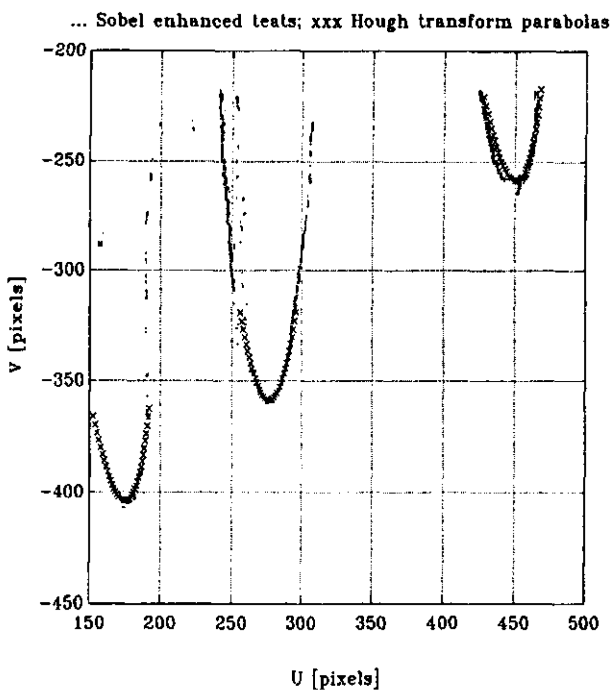


FIGURE 3.9b: Edge enhanced image and Hough transform parabolas of four large brown teats

FIGURE 3.10a: Grey-scale image of four small black teats

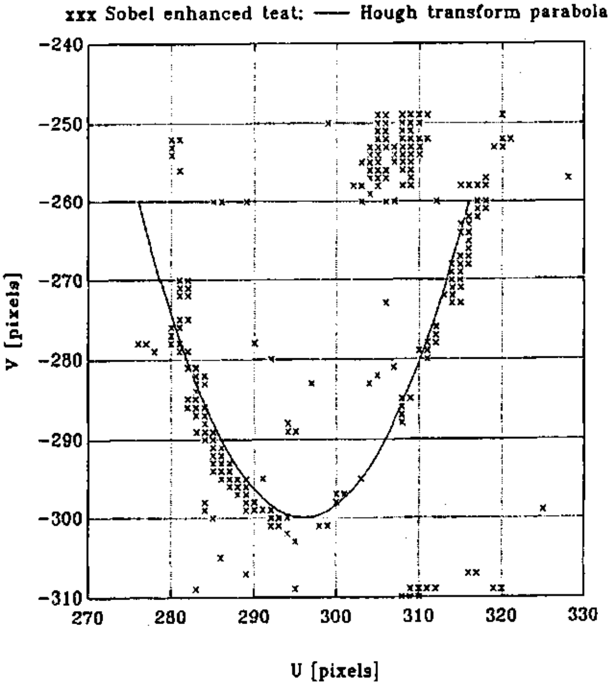


FIGURE 3.10b: Edge enhanced image and Hough transform parabola of left rear small black teat

FIGURE 3.11a: Grey-scale image of four medium sized whitish teats

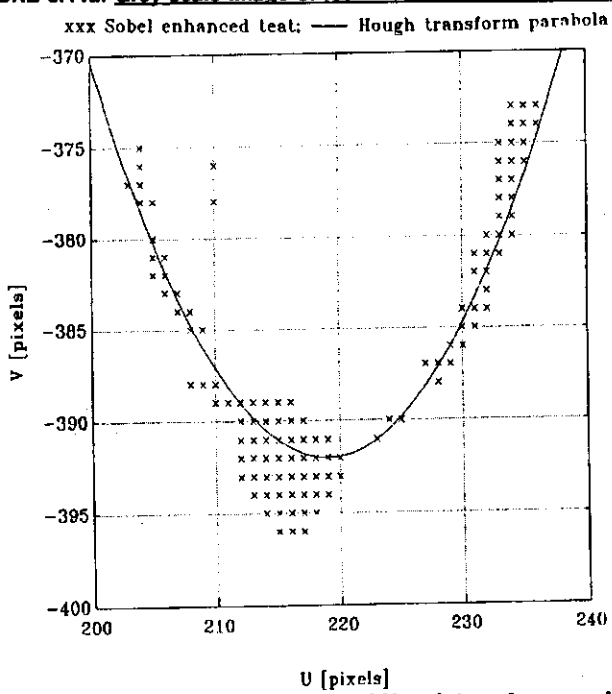


FIGURE 3.11b: Edge enhanced image and Hough transform parabola of right front medium white teat

3.4.4.6 CONCLUSIONS ON FINDING SCENE FEATURES FOR THE MILKING ROBOT

In the aforegoing parts of Section 3.4.4, a number of concepts for finding scene features in an image were discussed. A qualitative choice reduction was performed, and the **parabolic Hough transform** was investigated in detail. From experimental results it was concluded that this transform is definitely feasible for localising a cow's teats in edge enhanced images - although research is still required in order to overcome the following problem areas:

a. The parabolic Hough transform is computationally intensive, making it slow. (It should be possible to solve this problem by making use of parallel processing though.)

b. The parabolic Hough transform is computer memory intensive. With the current experimental set-up this problem necessitated the manual segmentation of images in order to provide smaller data sets than that obtained from a full 512 x 512 pixel image. (Since the development of computer hardware takes place so rapidly, it is however anticipated that computer technology will overtake this problem soon.)

c. The parabolic Hough transform requires a large four-dimensional accumulator array to be used. (Typically with dimensions in the order of 10 x 90 x 500 x 500.) Although possible in principle, the implementation of such an array is not an easy task. In this research it was implemented as multiple two-dimensional arrays, but with the disadvantage that multiple parabolas in the same image could not be localised. For a milking robot, this ability is essential. (This problem is related to the memory problem discussed in (b) above; and its solution should also come with new developments in computer technology.)

d. A threshold needs to be defined in order to classify entries in the accumulator array as possible parabolas or not. Proper criteria and procedures for the automatic determination of a suitable threshold need to be defined.

None of the above problems negate the feasibility of the parabolic Hough transform however - as demonstrated experimentally. Through further research and development, its ability for finding scene features in images for a milking robot can definitely be improved.

3.4.5 STEREO CORRELATION

For stereo vision it is essential that the measured coordinates in one image of an object must be correlated with the measured coordinates of the same object in the other image. Errors due to incorrect matching can easily occur in cases where similar objects appear in the images. Over the years, a number of techniques had been developed for correlating points in stereo images. Examples of these techniques are presented by HOFF & AHUJA (1989) - relative displacement or disparity in the position of objects; MARR & POGGIO (1979) - based on human stereo vision; MOHAN et al (1989) - disparity; and YAKIMOVSKY & CUNNINGHAM (1978) - comparison of grey levels in two stereo images, for correlation. (Refer to Appendix G - under *Stereo Vision* - for a list of literature references.) Many researchers however agree that stereo correlation is a rather difficult part of stereo machine vision. Some examples of such views are: *"[...] the correspondence problem, has been considered to be the central and the most difficult part of the stereo problem"* - HOFF & AHUJA (1990, p.121); *"The most difficult task in stereo is that of identifying corresponding locations in the two images"* - MOHAN et al (1989, p.113); and *"A main problem with stereo analysis is to detect disparities over a large range of values"* - OLSEN (1990, p.309).

3.4.5.1 STEREO CORRELATION FOR THE MILKING ROBOT

On the one hand stereo correlation for the milking robot is simplified by the fact that there are only four teats in each image, which have to be matched. On the other hand it is complicated because the four teats have similar features, and can easily be confused. Ideally, for localising the cow's teats, four pairs of left image coordinates, and four pairs of right image coordinates will be determined for the four teat endpoints, by means of the two cameras. If the four teats appear in the same order in the two images, correspondence will be easy, since the first pair of left image coordinates can be matched with the first pair of right image coordinates, etc.: $(U_{l1};V_{l1}) \leftrightarrow (U_{r1};V_{r1})$; $(U_{l2};V_{l2}) \leftrightarrow (U_{r2};V_{r2})$; $(U_{l3};V_{l3}) \leftrightarrow (U_{r3};V_{r3})$; $(U_{l4};V_{l4}) \leftrightarrow (U_{r4};V_{r4})$. Under such conditions, it is straightforward to calculate the world coordinates of the four teat endpoints, by making use of equation (3.13).

The above approach fails if the teats do not appear in the same order in the two images, or if one or more of the teats are occluded in one or both the images. In the next section, a solution for the first of the above two problems is presented.

Occlusion is a more serious problem, for which there is no easy solution. For the milking robot, the possibility of occlusion of one teat by another is largely reduced by appropriate placement of the cameras (e.g. by viewing the udder slightly from below instead of horizontally; and if the lines of sight of the two cameras are in the order of 45° to 60° relative to the cow's length). The possibility of occlusion of teats by those teatcups already attached, can also be reduced by implementing a well-defined strategy for attaching the teatcups - as discussed in Section 3.4.3.1.1 above. Another potential solution to the problem of occlusion - which was not investigated experimentally during this research - can be to displace the cameras incrementally (e.g. SCHALKOFF (1982a,b)) until four teat endpoints are found in each image. This can however become a time consuming and computer intensive process. Furthermore, since the camera parameters will change if the cameras are displaced, the cameras will have to be calibrated in specific positions, and the incremental displacements will have to be restricted to these positions only.

3.4.5.2 STEREO CORRELATION WHERE THE ORDER OF OBJECTS ARE NOT NECESSARILY THE SAME IN THE TWO IMAGES

3.4.5.2.1 Background

For a left and a right camera - with camera parameters $\alpha_{1,2,...,12}$ and $\beta_{1,2,...,12}$, and image coordinates (U_l,V_l) and (U_r,V_r) respectively - equations (3.8a) and (3.8b) can be rewritten as in (3.24).

$$a_1x + b_1y + c_1z + d_1 = 0 \quad (3.24a)$$
$$a_2x + b_2y + c_2z + d_2 = 0 \quad (3.24b)$$
$$a_3x + b_3y + c_3z + d_3 = 0 \quad (3.24c)$$
$$a_4x + b_4y + c_4z + d_4 = 0 \quad (3.24d)$$

with:-

$$\begin{aligned}
a_1 &= \alpha_1 - \alpha_9 U_l \\
b_1 &= \alpha_2 - \alpha_{10} U_l \\
c_1 &= \alpha_3 - \alpha_{11} U_l \\
d_1 &= \alpha_4 - \alpha_{12} U_l \\
a_2 &= \alpha_5 - \alpha_9 V_l \\
b_2 &= \alpha_6 - \alpha_{10} V_l \\
c_2 &= \alpha_7 - \alpha_{11} V_l \\
d_2 &= \alpha_8 - \alpha_{12} V_l \\
a_3 &= \beta_1 - \beta_9 U_r \\
b_3 &= \beta_2 - \beta_{10} U_r \\
c_3 &= \beta_3 - \beta_{11} U_r \\
d_3 &= \beta_4 - \beta_{12} U_r \\
a_4 &= \beta_5 - \beta_9 V_r \\
b_4 &= \beta_6 - \beta_{10} V_r \\
c_4 &= \beta_7 - \beta_{11} V_r \\
d_4 &= \beta_8 - \beta_{12} V_r
\end{aligned} \quad (3.25)$$

The matrix equations in (3.26) are derived from (3.24); and these equations represent values of y and z for specific values of x (provided that the camera parameters, and the image coordinates are known). These (x,y,z) values are somewhere on the line passing through the image point (on the camera's imaging plane), the camera's focus point, and the world point. For the x value of the world point, (3.26a) and (3.26b) will render the (y,z) values of the world point. For any other value of x, (3.26a) and (3.26b) will render the (y,z) values at the point where the line between the image point and the world point intersects the y-z plane at that specific value of x. For example, for $x = 0$, (3.26a) will determine the (y,z) values at the point where the line between the left camera's image point and the world point intersects the y-z plane at the origin of the world coordinates. In (3.26a) and (3.26b), y_l and z_l will equal y_r and z_r - and these values of y and z will be the world coordinates of the point under consideration - only if $x_l = x_r = x$ (where x is the true world coordinate of the point under consideration).

Once the image coordinates of the target objects (the teat endpoints in the case of a milking robot) had been determined in both the images, stereo correlation can be done as follows:

a. Use the left camera's two-dimensional model in (3.26a) and the image coordinates of the target points in the left image, to calculate the (y,z) world coordinates of each target point, at $x = 0$.

b. Use the right camera's two-dimensional model in (3.26b) and the image coordinates of the target points in the right image, to calculate the (y,z) world coordinates of each target point, at $x = 0$.

c. Compare the above two sets of (y,z) values, in order to find possible correspondences. (Differences will definitely occur, because the two sets of (y,z) values are calculated for

$$\begin{bmatrix} y_l \\ z_l \end{bmatrix} = \begin{bmatrix} b_1 & c_1 \\ b_2 & c_2 \end{bmatrix}^{-1} \begin{bmatrix} -a_1 x_l - d_1 \\ -a_2 x_l - d_2 \end{bmatrix} \quad (3.26a)$$

$$\begin{bmatrix} y_r \\ z_r \end{bmatrix} = \begin{bmatrix} b_3 & c_3 \\ b_4 & c_4 \end{bmatrix}^{-1} \begin{bmatrix} -a_3 x_r - d_3 \\ -a_4 x_r - d_4 \end{bmatrix} \quad (3.26b)$$

x = 0, which in general is not the true x-coordinate of the world points under consideration. (This value for x is merely a guess - used as a starting point.)

d. Unless a clear correspondence between the two sets of values is obtained, the above procedure is repeated at other values of x - chosen within the typical range of x.

e. Through the above steps, it should be possible to match each pair of measured image coordinates in the left image with a pair of measured image coordinates in the right image. Stereo correlation can thus be done, as long as all target objects are visible in both images - even if the order of objects differ in the two images.

3.4.5.2.2 Experimental results with stereo correlation by means of two-dimensional camera models

The above stereo correlation technique was evaluated by making use of the data in Table 3.6 (where the images of the twelve sticks did not occur in the same order in the two images - as can be verified by checking the two images' U-coordinates in Table 3.6). The results of this experiment are shown in Table 3.16 - determined by executing the following procedure:

a. Choose typical values of x. Based on *a priori* knowledge of the typical range of x, the values 0, 100, 200, 300, 400, and 500 are chosen.

b. Determine $y_{left}(k)$ and $z_{left}(k)$ from (3.26a); and $y_{right}(k)$ and $z_{right}(k)$ from (3.26b). (k = 1 to 12, because there are 12 points in Table 3.6.)

c. For each value of x: determine the best correlation between a specific y_{right} and the twelve calculated values of y_{left}. Repeat this for all twelve calculated values of y_{right}. (Number of comparisons done: number of x values, times number of y_{right} values, times number of y_{left} values = 6 x 12 x 12 = 864.)

d. Determine the indexes of y_{right} and y_{left} where the best correlation occurs, and mark these positions in a matrix. (The experimental results are shown in Table 3.16a. The marking was done by using the six values of x.)

e. Repeat steps (c) and (d) for the calculated z_{right} and z_{left} values. (The experimental results are shown in Table 3.16b.)

f. The number of "votes" indicated in Tables 3.16a and 3.16b are summed in Table 3.16c. From Table 3.16c the correlation between image coordinates in the left image and that in the right image is clear.

	y_{right} (1)	y_{right} (2)	y_{right} (3)	y_{right} (4)	y_{right} (5)	y_{right} (6)	y_{right} (7)	y_{right} (8)	y_{right} (9)	y_{right} (10)	y_{right} (11)	y_{right} (12)
y_{left} (1)	0 100 200 300 400 500	500										
y_{left} (2)		0 100	200 300 400									
y_{left} (3)		200 300 400	500									
y_{left} (4)			0 100	100 200 300 400 500	400 500							
y_{left} (5)					0 100	200 300	500					
y_{left} (6)				0	200 300	400 500						
y_{left} (7)						0 100	200 300 400	300 400 500				
y_{left} (8)								100	200 300	200 400		
y_{left} (9)							0 100	200	400 500	500		
y_{left} (10)								0	100	200	400 500	
y_{left} (11)											0 100	0 100 200
y_{left} (12)									0	0 100	200 300	300 400 500

TABLE 3.16a: Matching of calculated y-coordinates (left and right image). for different values of x

	z_{right} (1)	z_{right} (2)	z_{right} (3)	z_{right} (4)	z_{right} (5)	z_{right} (6)	z_{right} (7)	z_{right} (8)	z_{right} (9)	z_{right} (10)	z_{right} (11)	z_{right} (12)
z_{left} (1)	0 100 200 300 400 500											
z_{left} (2)		0 100 200 300 400 500										
z_{left} (3)			0 100 200 300 400 500									
z_{left} (4)				0 100 200 300 400 500								
z_{left} (5)					100 200 300 400 500							
z_{left} (6)						0 100 200 300 400 500						
z_{left} (7)							0 100 200 300 400 500					
z_{left} (8)								0 100 200				0 100 200
z_{left} (9)					0				0 100 200 300 400 500			
z_{left} (10)										0 100 200 300 400 500		
z_{left} (11)											0 100 200 300 400 500	
z_{left} (12)								300 400 500				300 400 500

TABLE 3.16b: Matching of calculated z-coordinates (left and right image), for different values of x

	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	R_{10}	R_{11}	R_{12}
L_1	12	1										
L_2		8	3									
L_3		3	7									
L_4			2	11	2							
L_5					7	2	1					
L_6				1	2	8						
L_7						2	9	3				
L_8								4	2	2		3
L_9					1		2	1	8	1		
L_{10}								1	1	7	2	
L_{11}											8	3
L_{12}								3	1	2	2	6

TABLE 3.16c: Matching of R = (U_r,V_r) with L = (U_l,V_l) - based on *voting* in Tables 3.16a and 3.16b

3.4.5.3 CONCLUSIONS ON THE FEASIBILITY OF STEREO CORRELATION BY MEANS OF TWO-DIMENSIONAL CAMERA MODELS

Stereo correlation by means of two-dimensional camera models renders good results, and the method is relatively simple. The method is computationally intensive though, but parallel processing can streamline it. Therefore it can be concluded that this technique is feasible for implementation as part of the milking robot - provided that no occlusion of teats occur.

3.5 CONCLUSIONS

In this chapter, machine perception was analyzed, with the aim of using it as part of a milking robot. The machine perception subsystem for a milking robot was divided into two segments, namely the **sensors**; and the **signal processor**.

From a trade-off study, a **television camera** was found to be the most suitable sensor to satisfy the specific technical performance requirements which were defined for a milking robot. A television camera can be characterized in terms of two transformations, namely the *geometric transformation* (from the three-dimensional world coordinates of points to the two-dimensional image coordinates); and an *electronic transformation* (from light intensity to an array of electronic signals - used by the signal processor). Since the exact characteristics of the geometric transformation are required for scene description, camera modelling and camera calibration were addressed in detail - both theoretically and experimentally.

Since a television camera was chosen as the main sensor, the signal processor is only concerned with **image processing** techniques. The primary task of the milking robot's image processor was defined as deriving a computerized description of the spatial positions of the endpoints of a cow's four teats, by making use of the camera models, and of images of the cow's udder and teats.

The main results obtained regarding the image processor and the scene description process are:

a. The feasibility of two-dimensional scene description for the milking robot was first investigated. With this concept the teats are viewed from below, with the aim of determining the endpoint positions in the horizontal plane. The teatcups can then be moved to these coordinates (well below the udder) and then be moved upwards until the teats are sucked in. From experiments with points marked on a flat plate, it was concluded that this concept could work, but in practice it was found that there was too little colour contrast between the teats and the udder of most cows. The teats could therefore not be distinguished from the udder, and the concept was therefore discarded. (In view of the potential advantages listed in Section 3.4.3.1.1, this concept should however be investigated further in future.)

b. The next step was to investigate the feasibility of three-dimensional scene description for the milking robot. The camera model described by BALLARD & BROWN (1982) was chosen (because of its relative simplicity); and the geometrical transformation parameters of two cameras in an experimental set-up, were determined. Different calculation routes for determining the three-dimensional world coordinates (x,y,z) of a point - based on the camera models and parameters, and a stereo pair of two-dimensional image coordinates - were defined, and verified experimentally. From the good results obtained, it was concluded that three-dimensional scene description is a feasible concept for use as part of a milking robot.

c. Localisation accuracy is of major importance for the milking robot's machine perception subsystem. The main potential contributors to localisation inaccuracies with a three-dimensional vision system were investigated experimentally and analytically. It was concluded that accurate camera calibration, and accurate determination of image coordinates are essential in order to ensure acceptable localisation accuracies. The need for further research regarding the optimal placement of cameras in a stereo-vision set-up, was also pointed out.

d. Before a cow's teats can be localised in terms of world coordinates through scene description, they must first be localised accurately (in terms of image coordinates) in the two images of the udder. After a discussion of different techniques for finding scene features, it was hypothesized that the edge enhanced images of a cow's teats resembled parabolas, and that the parabolic Hough transform could be used for localising teats in edge enhanced images. Although this technique is computer intensive, good experimental results were obtained, and it was concluded that this technique is indeed feasible. The main advantage of the Hough transform is its insensitivity to gaps in the edge enhanced image.

e. An important question in stereo vision deals with how to ascertain that the same object is located in both the images. An iterative stereo correlation method was proposed and evaluated experimentally - rendering good results.

Although a number of practical problems still exist with the implementation of three-dimensional scene description, with the parabolic Hough transform for localisation of a cow's teats in edge enhanced images, and with the use of two-dimensional camera models for stereo correlation, these problem areas are not of a fundamental nature. The processing speed for the machine perception subsystem proposed in this chapter, and implemented experimentally in an *IBM PC-AT compatible computer (80286 processor, and 80287 numerical co-processor)* is not fast enough to meet the absolute essential requirement of real-time localisation of a cow's teats - as specified in Section 2.3.3. All the proposed techniques are however well-suited for parallel processing - which should make the proposed system fast enough. This is an aspect which requires further research however.

The overall conclusion reached from the work presented in this chapter, is that three-dimensional scene description - based on the data derived from a stereo pair of television cameras - is feasible for implementation as part a milking robot.

CHAPTER 4

MECHANICAL MANIPULATION FOR A ROBOTIC MILKING MACHINE

4.1 INTRODUCTION

4.1.1 BACKGROUND

The main function of the manipulator subsystem of a robotic milking machine is to attach the four teatcups of a milking machine to the teats of a cow. (Since automatic removal of teatcups can be done by means of a vacuum release system, teatcup removal is not considered as part of the manipulator's functions.) The manipulator is defined to consist of four segments, namely the **robot arm**; the **robot hand** (or *end effector*); the **actuators**; and the **controller**.

Robotic technology is well advanced, and numerous manipulators are available commercially. It is however essential to first define and analyze the specific requirements to be met by a milking robot's manipulator; and then to custom-design a suitable manipulator to meet the peculiar requirements of a dairying environment. The results of this design process are presented in this chapter.

4.1.2 PURPOSE AND SCOPE OF CHAPTER

In this chapter, different concepts for each of the manipulator segments are identified, analyzed, and evaluated. In order to evaluate and compare different concepts for each segment (and its sub-segments) of the manipulator, technical requirements are identified for each of the segments; and each concept is then evaluated against the requirements. From this analysis, a suitable combination of manipulator concepts is chosen.

Because the different components of the manipulator influence each other, the analysis and synthesis process is iterative. This aspect slightly complicates the logic ordering of the chapter, and in some sections, information is used which is only derived and presented later in the chapter. These situations are however clearly indicated by means of cross references.

Similar to the presentation in Chapter 3, this chapter contains analytical discussions of numerous concepts for the different manipulator segments. Explanations are presented regarding the concepts which were found unfeasible for the milking robot; while a design incorporating the feasible concepts, is presented.

4.1.3 IMPLEMENTATION OF AN EXPERIMENTAL MANIPULATOR

An experimental manipulator was not implemented as part of this research. A suitable manipulator subsystem was however designed, and simulated - with the details presented in this chapter and in Appendix F. This research represents *concept exploration*, and not *full-scale development*. Therefore the emphasis is on the systematic investigation of different concepts and on the illustration of principles. There is no doubt that an experimental manipulator will have to be built as a next step, for validation of the milking robot concept presented. However, the main reasons for not implementing an experimental manipulator subsystem at this stage, are the following:

a. Enough information could be obtained from designing and simulating the manipulator's dynamic response, in order to verify the feasibility of the manipulation of a milking machine's teatcups by means of a mechanical manipulator.

b. Before the designed robot arm and robot hand are actually constructed, it will be very useful to simulate its kinematics by means of computer-aided animation - e.g. EYDGAHI & SHEEHAN (1991). Computer-aided animation however requires a substantial effort (representing a large field of study on its own) and it was therefore not addressed as part of the current work.

c. Since this research was done by a *'one-man team'*, available funds and time were limited.

4.2 THE ROBOT ARM

4.2.1 TECHNICAL PERFORMANCE REQUIREMENTS FOR THE ROBOT ARM

In this section a number of **technical performance requirements** which must be satisfied by the robot arm of a milking robot, are defined and compared with each other in order to determine their relative importance. The parameters defined are necessarily based on the author's own experience in the fields of system design and dairying. The defined parameters are the most important ones, and are not intended to be the alpha and the omega of milking robot requirements. Also note that life cycle cost and acquisition schedule are not included in this discussion, since the focus is on the *exploration of technical ability*.

The different requirements against which the sensor concepts are evaluated, influence each other. Although the requirements can thus not be considered in isolation, the aim is to decouple them as far as possible, and to analyze the robot arm concepts against one requirement at a time.

4.2.1.1 DEFINITION OF PERFORMANCE REQUIREMENTS

The most important technical performance requirements which must be satisfied by the robot arm of a milking robot, are:

a. Kinematic and dynamic ability. In order to utilize the adaptability of a robotic system, it was decided to use a single arm which will attach the four teatcups consecutively, in a pre-defined order. When the cow is ready in the stall, the teatcups will be moved in underneath the cow's udder, in a floor-level module on rails (with a control system separate from that of the milking robot). The robot hand will then move in underneath the cow, fetch a teatcup from the retainer module, move towards the teat's endpoint, and then move upwards until the teat is sucked in by the teatcup. The robot arm will then repeat the last three actions, before it moves out from under the cow, to its rest position. From the above it is clear that a robot arm with three degrees of freedom is required. Furthermore, the endpoint position must be controllable by means of simple control laws, in order to allow for fast response by the arm and its controller. (The complexity of the control laws influence the reaction time of the arm, because the more complex the control law, the more calculations have to be done by the controller.)

b. Action volume. The *action volume* of a milking robot defines all the points which the robot arm's endpoint must be able to reach - which are all those points where the cow's teats can possibly be, while she is waiting to be milked. The action volume must be dimensioned relative to the arm's mounting point. In order to determine the maximum reaching distances required for a milking robot, measurements were done by the author, for 20 Friesian cows standing ready to be milked. (The 20 cows were randomly chosen from a herd of about 300 animals - thus providing a fair statistical sample.) The detail of the measurements are not presented here, since the aim of the measurements was only to obtain an indication (within an accuracy of ± 25 mm) of the required reaching distances. (Since Friesian cows - one of the largest breeds of dairy cows - were used for the measurements, the action volume thus specified will be adequate for smaller breeds of cows as well.) Based on the said measurements, it was concluded that a robot arm with its base plate mounted on the side of the stall (at floor level), and about one third of the stall's length from its rear end, must reach at least 700 mm x 700 mm x 700 mm along three orthogonal axes. The abovementioned (crude) measurements were verified analytically, by making use of data on livestock dimensions - ASAE (1987a); data on stall sizes - ASAE (1987b) and MATON & DAELEMANS (1976, p.142); data on udder and teat dimensions - ORDOLFF (1983) and POLITIEK (1987); and data on reach distances for cows in the stall - MAATJE & SWIERSTRA (1977). Most of the data used was presented in terms of average (μ) and standard deviation (σ) values. For a Gaussian distribution, statistical tables - e.g. STOKER (1977) - indicate that 99,73% of measurements will have values in the range $\mu \pm 3\sigma$. The maximum value of such a statistically measured parameter can thus be assumed to be $\mu + 3\sigma$. Based on the measurements by ORDOLFF (1983) and POLITIEK (1987), GOUWS (1988g) calculated the maximum distance ($\mu+3\sigma$) between a Dutch Friesian cow's front teats to be 344 mm. The width of a typical stall is 900 mm - MATON & DAELEMANS (1976, p.142). As indicated in Section 2.4.1, there are different mechanisms available to centre a cow in the stall. With the cow centred, the maximum distance from the stall's one side to the front teat on the opposite side of the udder is half the stall width plus half the distance between the front teats (which are normally further apart than the rear teats) - i.e. 900/2 + 344/2 = 622 mm. The length of a typical stall is 2400 mm - MATON & DAELEMANS (1976, p.142); while the maximum length of a typical Holstein cow is about 2000 mm - ASAE (1987a, p.393). Since Dutch Friesians are slightly larger than Holsteins, the maximum length of a cow is taken as 2200 mm. The udder is located in the rear quarter of the cow's length (i.e. approximately 500 to 550 mm measured from her tail end). If a stall with a moving front end is used (e.g. MONTALESCOT & MECHINEAU (1987)), a robot arm with a reaching distance of 700 mm, and mounted a third of the stall's length from the rear end of the stall, will be able to reach the rear teats of all cows. Based on the measurements by ORDOLFF (1983) and POLITIEK (1987), GOUWS (1988g) calculated the maximum distance ($\mu+3\sigma$) between a Dutch Friesian cow's front udder and the floor level to be 625 mm. By making use of the extensive data available in the literature, the action volume (700 mm x 700 mm x 700 mm) derived from the crude measurements performed by the author, were thus confirmed to be adequate.

c. Installation space required. The robot arm should not require excessive installation space; and it should not obstruct the cow's entry into, or her exit from the stall in any way due to its installation configuration.

d. Steady state position error. The steady state position error of the milking robot's manipulator subsystem, is due to bending of the arm segments; nonlinearities (e.g. a dead zone in the controller, mechanical backlash, and nonlinear friction) not fully compensated for by the control system; and steady state error due to the control system *type* (refer to SHINNERS (1979, p.167). In order to determine an acceptable steady state error for the position control system, discussions were held with experienced dairy farmers; experienced human milkers were watched while attaching milking machines to cows; and the author performed experimental measurements involving the 20 cows used for the action volume measurements (refer to Section 3.4.2 for a description of these measurements). From this it was found that with differences of up to 10 mm in the horizontal plane, between the actual position of a teat's endpoint, and the centreline of the teatcup's opening, the teat was still sucked into the teatcup, when the teatcup was moved upwards. This is mainly due to the typical tapered form of cows' teats, as well as to the suction of the milking machine's vacuum system. (Teatcups with wider-than-normal openings - refer to Section 2.4.2 - will work even better in this regard.) In Section 3.4.2 it was decided to allocate an error of 4,3 mm to the manipulator subsystem. This implies that a positioning error in the order of 4 mm in the horizontal plane, due to the manipulator subsystem, can be tolerated.

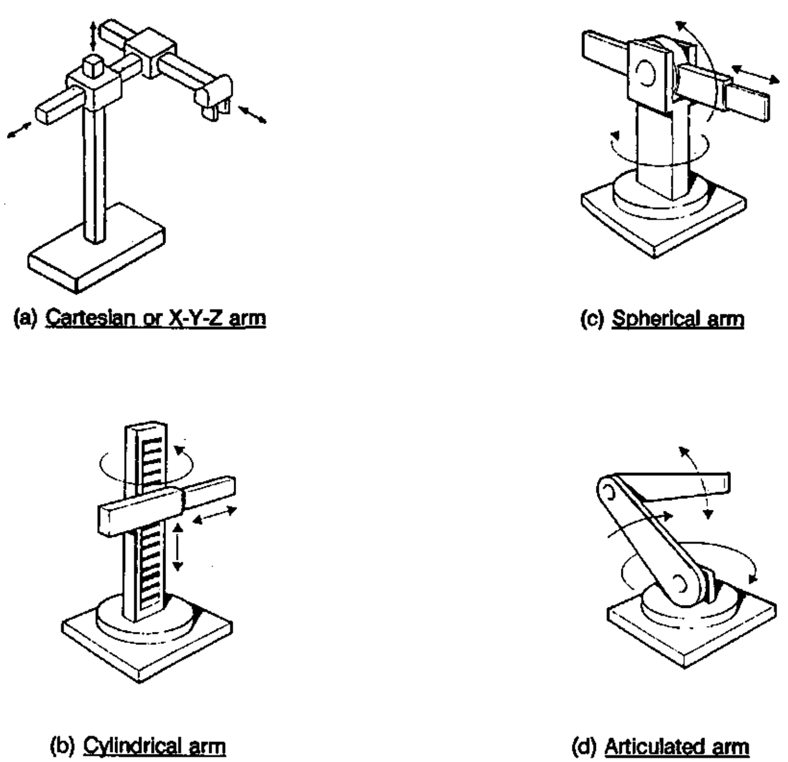
d. Robustness and environmental compatibility. A dairying environment can never be kept absolutely clean or dry - therefore the robot arm must be able to withstand these environmental conditions. The environmental conditions therefore rule out the use of very fine gear drives, or materials that are not water resistant, for example. (Since the use of a mechanism for restricting the movements of a cow in the stall is considered an essential part of a robotic milking system, kicking by the cow is not considered as a major problem for the robot arm. The arm must however be able to survive light contact with a cow.)

4.2.1.2 WEIGHTING OF PERFORMANCE REQUIREMENTS

In Table 4.1 the different technical performance parameters for the robot arm (as defined in Section 4.2.1.1) are compared with each other, in order to determine their relative importance - indicated by the *weight* factor. (Remember that life cycle cost and development schedule are not used as performance parameters here, since the focus is on the technical appropriateness of the different concepts.) The weighting is done as explained for Table 3.1 in Section 3.2.1.2.

	Kinematic and dynamic ability	Action volume	Installation space required	Steady state position error	Robustness and environmental compatibility
Kinematic and dynamic ability	-	3	3	4	5
Action volume	7	-	4	5	5
Installation space required	7	6	-	5	6
Steady state position error	6	5	5	-	5
Robustness and environmental compatibility	5	5	4	5	-
Sum of components	25	19	16	19	21
Weight (%)	25	19	16	19	21

TABLE 4.1: Determination of relative weights for robot arm trade-off parameters



(a) Cartesian or X-Y-Z arm

(c) Spherical arm

(b) Cylindrical arm

(d) Articulated arm

FIGURE 4.1: Robot arm configurations with three degrees of freedom

4.2.2 IDENTIFICATION OF ROBOT ARM CONCEPTS

Four common robot arm configurations with three degrees of freedom, are shown in Figure 4.1.

4.2.2.1 CARTESIAN OR X-Y-Z ROBOT ARM

The cartesian arm has three independent, and linear axes of movement. The coordinates of the arm's endpoint (refer to Figures 4.1a and 4.2) are:

$$x = a \tag{4.1}$$
$$y = b \tag{4.2}$$
$$z = -c \tag{4.3}$$

The values of a, b and c are independently controlled by the movements of the arm's three actuators. The minima and maxima of these values depend on the construction of the robot arm.

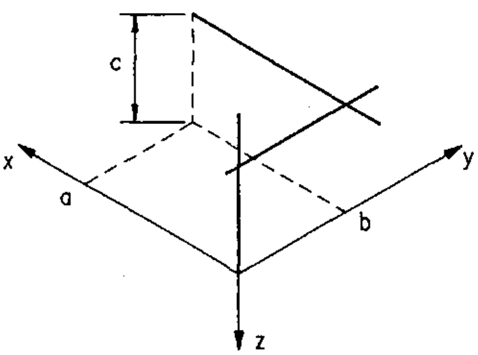


FIGURE 4.2: Coordinates of a cartesian robot arm

4.2.2.2 CYLINDRICAL ROBOT ARM

The cylindrical robot arm has two linear axes and one rotating wrist. The coordinates of the arm's endpoint (refer to Figures 4.1b and 4.3) are:

$$x = r \cos \theta \tag{4.4}$$
$$y = r \sin \theta \tag{4.5}$$
$$z = -c \tag{4.6}$$

The values of c, r and θ are controlled by the movements of the arm's three actuators. The minima and maxima of these values depend on the construction of the robot arm. The values of the X-coordinate and the Y-coordinate are interdependent - being functions of r and θ. (Each of these coordinates thus depends on the movements of two actuators.) The Z-coordinate however, is independent of the other two, and depends on the movement of only one actuator.

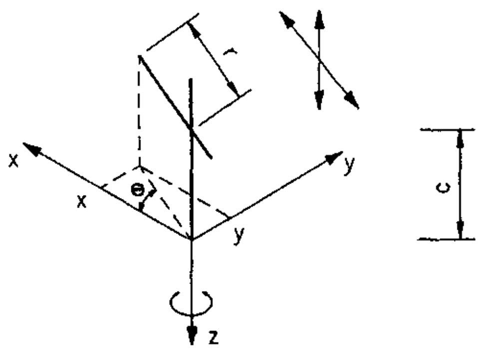


FIGURE 4.3: Coordinates of a cylindrical robot arm

4.2.2.3 SPHERICAL ROBOT ARM

The spherical robot arm has one linear axis and two rotating wrists. The coordinates of the arm's endpoint (refer to Figures 4.1c and 4.4) are:

$$x = r (\cos \alpha)(\cos \theta) \tag{4.7}$$
$$y = r (\cos \alpha)(\sin \theta) \tag{4.8}$$
$$z = -r (\sin \alpha) \tag{4.9}$$

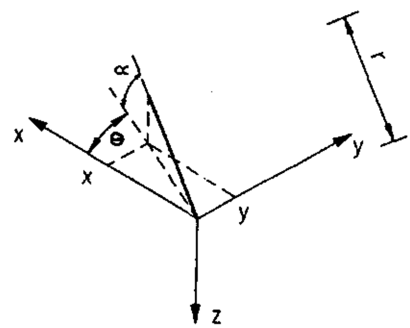


FIGURE 4.4: Coordinates of a spherical robot arm

The values of r, α and θ are controlled by the movements of the arm's three actuators. The minima and maxima of these values depend on the construction of the robot arm. The values of the three coordinates are interdependent. The

X- and the Y-coordinate depend on the movements of all three actuators, while the Z-coordinate depends on the movements of two of the three actuators.

4.2.2.4 ARTICULATED ROBOT ARM

The articulated robot arm has three rotating wrists. The coordinates of the arm's endpoint (refer to Figures 4.1d and 4.5) are:

$$x = (c_1 \cos \alpha + c_2 \cos \phi) \cos \Theta \quad (4.10)$$
$$y = (c_1 \cos \alpha + c_2 \cos \phi) \sin \Theta \quad (4.11)$$
$$z = -(c_1 \sin \alpha + c_2 \sin \phi) \quad (4.12)$$

The values of α, ϕ and Θ are controlled by the movements of the arm's three actuators. The minima and maxima of these values, and the values of c_1 and c_2 depend on the construction of the robot arm. The values of the three coordinates are interdependent. The X- and the Y-coordinate depend on the movements of all three actuators, while the Z-coordinate depends on the movements of two of the three actuators.

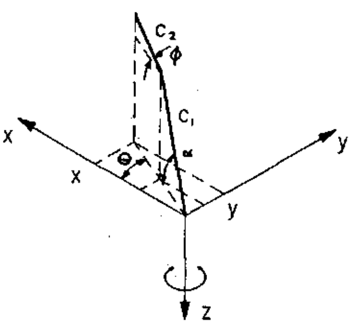


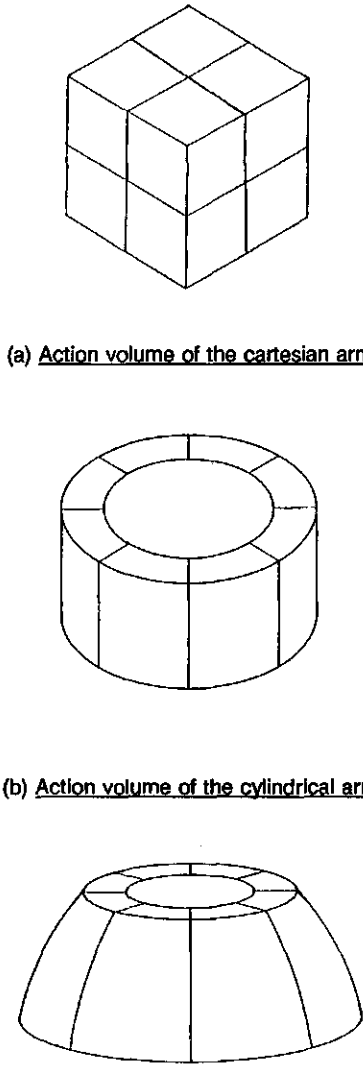
FIGURE 4.5: Coordinates of an articulated robot arm

4.2.2.5 ACTION VOLUME SHAPES

Figure 4.6 shows the shapes (which are referred to again in Table 4.2) of the action volumes for different arm configurations. The action volume of the articulated arm is a combination of that shown for the other three arms.

4.2.3 ANALYSIS OF ROBOT ARM CONCEPTS

This section contains a qualitative as well as a quantitative analysis of the different robot arm concepts identified in Section 4.2.2. (The analysis is similar to that performed in Section 3.2.3 for the different sensor concepts.)



(a) Action volume of the cartesian arm

(b) Action volume of the cylindrical arm

(c) Action volume of the spherical arm

FIGURE 4.6: Examples of action volumes

The ability of each concept to meet the requirements signified by the performance parameters defined in Section 4.2.1, is analyzed in Tables 4.2a through 4.2d. Based on the qualitative analysis presented in the third column of the table, each concept is rated with a value between 0 and 5 - as shown in the fourth column of the table. The following ratings are used:

0: *the concept is completely* **inadequate** to satisfy the requirements;
1: the concept is a **very poor** solution to *satisfy the requirements;*
2: the concept is a **poor** solution to satisfy the requirements;
3: *the concept is a* **reasonable / tolerable** solution to satisfy the requirements;
4: the concept is a **good** solution to satisfy the requirements;
5: the concept is an **ideal** solution to satisfy the requirements.

The second column of each table contains the *weight* - as allocated to each performance parameter in Table 4.1. The last column of each table contains the *weighted ratings*, which are the ratings in column 4, weighted by the parameter weights in column 2. The *weighted rating = weight x (rating/5)*. (In this formula, the rating is divided by the maximum rating 5, in order to normalize the answers.)

In order to remove possible bias of the author towards certain concepts, another engineer with extensive experience in such trade-off studies, was asked to repeat the complete trade-off process independently. The two sets of results were very similar, and were combined to form the results shown in Table 4.2.

From the trade-off results summarized in Table 4.3, it is clear that the four robot arm configurations should perform very similar when tested against the performance requirements defined in Section 4.2.1. The cartesian arm (Figure 4.1a) fared better than the other three arm configurations in the trade-off - mainly because its three axes are **independently controllable** (without the need to solve transcendental equations in the controller). Therefore the cartesian arm is chosen for further use in this research project. (It must again be emphasised that the trade-off process used cannot provide absolutely accurate answers, but it is merely a technique to ensure that different concepts are evaluated against the same requirements.)

4.2.4 DESIGN OF THE ROBOT ARM

4.2.4.1 FRAME OF REFERENCE

The robot arm must use the same frame of *reference than the orthogonal right handed* frame of reference (*"world coordinates"*) chosen for the machine vision subsystem.

In Section 4.2.1.1.b it was pointed out that a suitable mounting position for the robot arm's base plate is on the side of the stall; on the floor; and about one third of the stall's length from its rear end. For the sake of this discussion it is decided to mount the robot arm on the stall's right hand side. (It can however also work on the left hand side - with some changes in the definition of coordinates. In order to allow one milking robot to serve more than one stall, the robot can be mounted between two parallel stalls - in which case one cow will be milked from the right, and one from the left. Alternatively it can be mounted in the middle of a square formed by four stalls - in which case all four cows can be milked from the same side; thus allowing for the same axes convention to be used through-out.)

Based on the above information, the chosen frame of reference has the following characteristics:

a. Reference point: the geometrical centre of the robot arm's mounting point.

b. x-axis: horizontal; parallel with the length of the stall; and directed towards the stall's rear end.

c. y-axis: horizontal; and to the right (when looking from the robot arm towards the stall's rear end).

d. z-axis: vertical and downwards.

1	2	3	4	5
Performance parameter	Weight [%]	Qualitative Analysis of the Cartesian Arm for a Milking Robot	Quantitative Analysis	
			Rating (0-5)	Weighted rating
Kinematic and dynamic ability	25	Since the cartesian arm has three degrees of freedom, it satisfies the basic manoeuvrability requirements (i.e. moving in underneath the cow; fetching a teatcup; moving towards the x-y coordinates of the relevant teat; and then moving upwards). The three coordinates of the cartesian arm's endpoint can be controlled independently (refer to equations (4.1) to (4.3) above), and therefore the simultaneous control of the three axes is simple. When the desired (x,y,z) coordinates of the cartesian arm's endpoint are known, the actuator positions are very easy to calculate. For these reasons, the cartesian arm's control law is the simplest of the four arm concepts.	5	25
Action volume	19	The shape of a cartesian arm's action volume is shown in Figure 4.6a. The arm can thus easily be designed to comply with the requirements of an action volume of 700 mm x 700 mm x 700 mm.	5	19
Installation space required	16	With the cartesian robot arm mounted on the floor and on the side of the stall, and with the two horizontal arm segments completely retracted from the stall area, the cartesian arm will not hamper the cow's movements into or from the stall. The two horizontal arm segments cannot be folded away, they can only move to different places (unless telescopic arm segments are used - but that will imply other problems such as decreased arm rigidity). The maximum footprint of an arm as shown in Figure 4.1a will be T-shaped. For the desired action volume of 700 mm x 700 mm x 700 mm, the total travelling space required for the vertical stroke of the T will be about 1400 mm; while that for the horizontal stroke of the T will be about 1400 mm wide, and 700 mm high.	3	10
Steady state position error	19	The cartesian arm will have a steady state position error, depending on the static bending of the arm segments, and on the characteristics of the three actuators' control loops. There is will be much different from that of the other arm concepts.	4	15
Robustness and environmental compatibility	21	There is nothing to suggest that the cartesian arm will withstand water, dust, and dirt in its environment differently from the other concepts. Since it has linearly moving arm segments, the arm segments can be damaged if leaned against by a cow, orthogonally to the normal direction of movement.	3	13
	100			82

TABLE 4.2a: Analysis of a cartesian arm for the milking robot

1	2	3	4	5
Performance parameter	Weight [%]	Qualitative Analysis of the Cylindrical Arm for a Milking Robot	Quantitative Analysis	
			Rating (0-5)	Weighted rating
Kinematic and dynamic ability	25	Since the cylindrical arm has three degrees of freedom, it also satisfies the basic manoeuvrability requirements. Because of the trigonometric relationships in equations (4.4) to (4.6), transcendental equations must be solved in order to determine the actuator positions from the desired (x,y,z) coordinates of the arm's endpoint. Such calculations are normally computer intensive. Two of the three coordinates of the cylindrical arm's endpoint are also interdependent, making the cylindrical arm's control more complex than that of the cartesian arm. (Control of interdependent coordinates is discussed by THRING (1983, p.113), as *"The problem of decoupling"*.)	4	20
Action volume	19	The shape of a cylindrical arm's action volume is shown in Figure 4.6b. The arm can by definition only reach points in a cylinder. Although the required action volume is specified in Section 4.2.1.2 as a cube, it is not absolutely essential to be a cube (or even rectangular). The cylindrical arm can however be designed to reach all the points in the specified cube, by designing it such that a section of the cylinder shown in Figure 4.6b is larger than the specified cubicle action volume. (This might require longer arm segments than for the cartesian arm.)	4	15
Installation space required	16	With the cylindrical robot arm mounted on the floor and on the side of the stall, it will not hamper the cow's movements into or from the stall, if the horizontal arm segment is parked parallel to the stall. The arm's maximum footprint is a circle, with its radius determined by the length of the horizontal arm segment. (The comments about telescopic arm segments for the cartesian arm also apply here.)	4	13
Steady state position error	19	The cylindrical arm will have a steady state position error, depending on the static bending of the arm segments, and on the characteristics of the three actuators' control loops. There is will be much different from that of the other arm concepts.	4	15
Robustness and environmental compatibility	21	There is nothing to suggest that the cylindrical arm will withstand water, dust, and dirt in its environment differently from the other concepts. Since it has one rotational wrist (around the upright section - refer to Figure 4.1b), its chances of being damaged by a cow leaning against it are slightly less than that of the cartesian arm. (Provided that the rotational wrist is fitted with some slip mechanism.)	3	13
	100			76

TABLE 4.2b: Analysis of a cylindrical arm for the milking robot

1	2	3	4	5
Performance parameter	Weight [%]	Qualitative Analysis of the Spherical Arm for a Milking Robot	Quantitative Analysis	
			Rating (0-5)	Weighted rating
Kinematic and dynamic ability	25	Since the spherical arm has three degrees of freedom, it also satisfies the basic manoeuvrability requirements. The three coordinates of the cartesian arm's endpoint are also interdependent, and described by trigonometric relationships - equations (4.7) to (4.9). Because of the specific trigonometric relationships, its control is more complex than that of the cylindrical arm.	3	15
Action volume	19	The shape of a spherical arm's action volume is shown in Figure 4.6c. The arm can by definition only reach points in a semi-sphere. Although the required action volume is specified as a cube, it is not absolutely essential to be a cube. If necessary, the spherical arm can - as the cylindrical arm - be designed to reach all the points in the specified cube. (This might require longer segments than for the cartesian arm.)	4	15
Installation space required	16	If the spherical arm is parked in parallel with the stall, it will render no obstruction for the cow's entry into, or her exit from the stall. The arm's footprint can be decreased by elevating the arm segment, but with an increase in the arm's height. The maximum footprint is also a circle, with its radius determined by the length of the arm segment. (The comments about telescopic arm segments for the cartesian arm also apply here.)	4	13
Steady state position error	19	The spherical arm will have a steady state position error, depending on the static bending of the arm segments, and on the characteristics of the three actuators' control loops. There is will be much different from that of the other arm concepts.	4	15
Robustness and environmental compatibility	21	There is nothing to suggest that the spherical arm will withstand water, dust, and dirt in its environment differently from the other concepts. Since it has two rotational wrists, its chances of being damaged by a cow leaning against it are less than that of the cylindrical arm. (Provided that the rotational wrists are fitted with some slip mechanism.)	4	17
	100			75

TABLE 4.2c: Analysis of a spherical arm for the milking robot

1	2	3	4	5
Performance parameter	Weight [%]	Qualitative Analysis of the Articulated Arm for a Milking Robot	Quantitative Analysis	
			Rating (0-5)	Weighted rating
Kinematic and dynamic ability	25	Since the articulated arm has three degrees of freedom, it also satisfies the basic manoeuvrability requirements. The three coordinates of the articulated arm's endpoint are also interdependent - equations (4.10) to (4.12). Because of the specific trigonometric relationships, its control is more complex than that of any of the other arm concepts.	2	10
Action volume	19	The shape of an articulated arm's action volume is a combination of that of the other three arms. The arm can be designed to comply with an action volume of 700 mm x 700 mm x 700 mm.	5	19
Installation space required	16	The articulated arm can be folded up such that it renders no obstruction for the cow's entry into, or her exit from the stall. When folded up, its footprint becomes very small, while its height will then be limited to the length of one of the arm segments (refer to Figure 4.1d). The arm however requires some space to perform its folding and unfolding actions; and thus the maximum footprint is also a circle with its radius determined by the sum of the lengths of the two arm segments.	4	13
Steady state position error	19	The articulated arm will have a steady state position error, depending on the static bending of the arm segments, and on the characteristics of the three actuators' control loops. There is will be much different from that of the other arm concepts.	4	15
Robustness and environmental compatibility	21	There is nothing to suggest that the articulated arm will withstand water, dust, and dirt in its environment differently from the other concepts. Since it has three rotational wrists, its chances of being damaged by a cow leaning against it are less than that of the spherical arm. (Provided that the rotational wrists are fitted with some slip mechanism.)	4	17
	100			74

TABLE 4.2d: Analysis of an articulated arm for the milking robot

Performance Parameters	Weight [%]	Cartesian Arm	Cylindrical Arm	Spherical Arm	Articulated Arm
Kinematic and dynamic ability	25	25	20	15	10
Action volume	19	19	15	15	19
Installation space required	16	10	13	13	13
Steady state position error	19	15	15	15	15
Robustness and environmental compatibility	21	13	13	17	17
TOTAL RATING [%]	100	82	76	75	74

TABLE 4.3: Summary of trade-off results for different robot arm concepts for the milking robot

4.2.4.2 ROBOT ARM DESIGN CONSIDERATIONS

In Section 4.2.3, a **cartesian robot** arm was chosen as a suitable configuration for the milking robot. Figure 4.7 shows a suitable cartesian arm for the milking robot. The following aspects are important for construction of the robot arm as shown in Figure 4.7:

a. Where reference is made to the x-, y-, and z-arm segments, these names refer to the specific cartesian arm configuration in Figure 4.7, and its chosen frame of reference. The z-arm segment is the vertical one; the y-arm segment is the horizontal one mounted to the z-arm segment; and the x-arm segment is the horizontal one to which the robot hand will be mounted.

b. Each arm segment has a bearing block around it. The z-arm segment is stationary, with its bearing block moving up and down. The other two arm segments move within their bearing blocks. In order to minimize friction between the arm segment and the bearing block, the arm segment will run on roller bearing supported shafts, mounted within the bearing block - as shown in Figure F.3 (Appendix F).

c. The actuators shall be mounted within sealed containers for protection against water, dust, and other adverse environmental conditions. (The y-arm segment's endpoint will fit over the x-arm segment's actuator - providing even better protection for this actuator.)

d. In order to ensure firm coupling between the arm segments and the bearing blocks, the arm segments shall be designed with square profiles.

e. In Section 4.2.1.1.b, it was decided that the milking robot's arm must reach 700 mm along the x-, the y-, and the z-axis (relative to its mounting position on the right hand side of the stall's floor).

4.2.4.3 MECHANICAL DESIGN OF THE ROBOT ARM

Appendix F contains the *constructional details* of a suitable arm for the milking robot. The design procedure followed has resulted in a cartesian arm (as shown in Figure 4.7), with the following mechanical characteristics:

a. Type of material for the arm segments: aluminium.

b. Reaching distance of each arm segment: 700 mm.

c. Mass of each arm segment: 1,65 kg.

d. Profile of each arm segment: hollow beam, with outer dimension of 50 mm; and inner dimension of 40 mm. For the x- and y-arm segments, the bottom side has a 5 mm wide slot, over the arm segment's full length (except for the last 20 mm on each side).

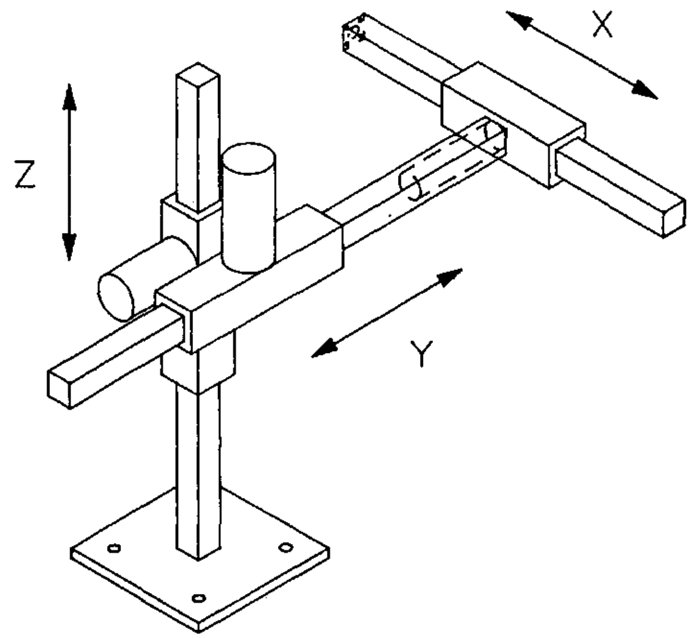


FIGURE 4.7: Configuration of a suitable arm for the milking robot

The z-arm segment is slotted similarly on one side (the analysis shows that it does not matter much on which side it is slotted).

e. Static error of the robot hand's x-position (due to loads acting on the arm segments): $x_e \approx 0{,}3$ mm.

f. Static error of the robot hand's y-position (due to loads acting on the arm segments): $y_e \approx 0{,}5$ mm.

g. Static error of the robot hand's z-position (due to loads acting on the arm segments): $z_e \approx 2{,}3$ mm.

The calculated error in the robot hand's z-position indicates that the hand will be slightly below the anticipated position. In Section 3.4.2 it was however pointed out that it is actually desirable to have the hand slightly below the teat's endpoint, before the hand starts moving upwards. The z-position error does therefore not cause any problems. The nett static error in the x-y (horizontal) plane is less than 1 mm. Such an error is well below the 4,3 mm manipulator error allowed - refer to Section 3.4.2. Furthermore, the calculated values represent the worst case scenario, and can therefore be accepted as it is.

4.3 THE ACTUATORS

Electrical-, hydraulic-, or pneumatic actuators are commonly used for robotic applications; and are discussed in this section. These actuators are used either for rotational, or for linear actuation. (Rotational actuators, in combination with screw drives, or similar devices, can be used to provide linear actuation.) The main disadvantage of linear actuators is the limited travel distance.

4.3.1 TYPE OF ACTUATOR

4.3.1.1 TECHNICAL PERFORMANCE REQUIREMENTS FOR THE ACTUATORS

In this section a number of technical requirements which must be satisfied by the actuators of a milking robot, are identified and discussed. Different actuator concepts are then evaluated in terms of these requirements. This analysis is similar to (but more extensive than) that presented by MARCHANT et al (1987).

4.3.1.1.1 Definition of performance requirements

a. Controllability of the actuators. The endpoint coordinates of a milking robot's arm must be controlled accurately. Unless the actuators can be well controlled, the required positional error of less than 4,3 mm - as defined in Section 3.4.2 - will not be attainable for the manipulator.

b. Mass, size, force, and speed of actuators. In order to limit the mass and size of the robot arm and the robot hand, the mass and size of the actuators should be restricted. The physical size of the actuator is however determined by the required actuator force (or torque) and speed of movement; which is in turn dictated by the load which must be moved by the actuator.

c. Environmental compatibility, robustness, hygiene, and washability. A dairying environment cannot be kept absolutely clean. In order to maintain hygienic conditions for the handling of milk, the milking machine and the milking robot must be washable with water, detergent, and disinfectant. Furthermore, the actuators must not collect excessive dirt by itself. The actuators of a milking robot must thus comply with the following requirements:
   i. It must be robust enough to withstand the typical environmental conditions of a dairying set-up.
   ii. It must be inherently clean and hygienic - i.e. an actuator should not be a collector of dirt.
   iii. It must be washable.

d. Availability of energy source. The availability of the required energy source to power the actuators is an important parameter to take into account when the actuator type is chosen.

4.3.1.1.2 Weighting of performance requirements

In Table 4.4 the different actuator requirements are compared with each other, in order to determine their relative importance (weight). (The comparison is done as explained for Table 3.1, in Section 3.2.1.2.)

	Controllability	Mass, size, force, and speed	Environmental compatibility	Availability of energy source
Controllability	-	3	5	4
Mass, size, force, and speed	7	-	6	4
Environmental compatibility	5	4	-	4
Availability of energy source	6	6	6	-
Sum of components	18	13	17	12
Weight (%)	30	22	28	20

TABLE 4.4: Determination of relative weights for the actuator trade-off parameters

4.3.1.2 IDENTIFICATION OF ACTUATOR TYPES

4.3.1.2.1 Electrical actuators

The most common electrical actuators are rotating electrical motors - of which the main types are alternating current-, direct current-, and stepper motors. The most important characteristics of electrical machines, which are of importance for a milking robot, are:

a. Electrical motors have simple designs, and are relatively easy to maintain.

b. Techniques for the control of these machines are well established.

c. Unless sealed machines are used, electrical short circuits can occur due to water or dust.

d. Electrical machines can be damaged when it stalls (unless protection is provided through the controller).

(Refer to FITZGERALD et al (1971); SAY (1976); and SAY & TAYLOR (1980), and the other literature listed under *Electrical Machines* in Appendix G, for more detailed discussions on electrical machines.)

4.3.1.2.2 Hydraulic actuators

Hydraulic actuators are commonly used as rotating- or as linear actuators. The most important characteristics of these actuators, as discussed by McCLOY & MARTIN (1980), and by STEWART (1978), are:

a. Hydraulic actuators normally have high power-to-mass ratios (due to typical working pressures in the order of 25 MPa).

b. Generally, hydraulic fluid has a high bulk modulus, resulting in a rigid system (i.e. no sluggish response).

c. Protection against over-pressure damage (e.g. when the machine stalls) is provided by means of pressure relief valves.

d. Maintenance of hydraulic systems requires very clean workshops.

e. Hydraulic fluid - with a regulated supply pressure - is required for the actuators.

f. Hydraulic systems tend to leak (mainly because of the high working pressures).

(Refer to the literature listed under *Fluid Systems* in Appendix G, for more detailed discussions on hydraulic machines.)

4.3.1.2.3 Pneumatic actuators

Pneumatic actuators are also commonly used as rotating- or as linear actuators. The most important characteristics of these actuators, as discussed by McCLOY & MARTIN (1980), are:

a. Lower power-to-mass ratios than for hydraulic actuators, due to typical pneumatic working pressures in the order of 200 to 1 200 kPa.

b. Air (or any other gas used in pneumatic actuators) is compressible, which can result in a sluggish system.

c. Protection against over-pressure damage (e.g. when the machine stalls) is provided by means of pressure relief valves.

d. Maintenance is relatively easy, since leaks are not serious, and since simple components are used for these actuators.

e. A regulated supply pressure (compressed air or gas, or a vacuum) is required for these actuators.

(Refer to the literature listed under *Fluid Systems* in Appendix G, for more detailed discussions of pneumatic machines.)

4.3.1.3 ANALYSIS OF THE ACTUATORS

Table 4.5 represents an analysis of the three actuator types - based on the defined actuator performance requirements. (Similar to that described in Section 3.2.3 for the sensor.)

4.3.1.4 CONCLUSIONS FROM THE ACTUATOR ANALYSIS

From the trade-off results in Table 4.5, it is concluded that **electrical actuators** are more suitable than hydraulic or pneumatic actuators to satisfy the defined actuator requirements for a milking robot. In order to meet the environmental compatibility requirements, it is however essential that **sealed** electrical actuators shall be used.

1	2	3	4	5
Performance parameter	Weight [%]	Qualitative Analysis of Electrical Actuators for a Milking Robot	Quantitative Analysis	
			Rating (0-5)	Weighted rating
Controllability	30	Electrical actuators are typically controlled via control of the power amplifier. Control techniques for these actuators are well established.	5	30
Mass, size, force, and speed	22	Since a teatcup and its pipes have a relatively low mass, the robot arm falls in the low power category - such that the actuators can easily be dimensioned to deliver the required force (or torque) and speed, and still be within suitable mass and size limits. It is relatively easy to remotely locate electrical switchgear; and electrical cables for a low power application will be small, with a low mass.	4	18
Environmental compatibility	28	An electrical actuator is inherently clean and hygienic. If a sealed machine is used, it is washable, and dust proof - i.e. it complies with the robustness requirements imposed by a dairying environment. (The cooling of sealed machines should not be a problem, since a milking robot's actuators are not required to operate continuously, and since the robot arm will act as a heat sink.)	4	22
Availability of energy source	20	Electricity forms an integral part of the infrastructure of a modern dairying set-up. Electrical power is also easily reticulated by means of cables.	5	20
	100			90

TABLE 4.5a: Analysis of electrical actuators for the milking robot

1	2	3	4	5
Performance parameter	Weight [%]	Qualitative Analysis of Hydraulic Actuators for a Milking Robot	Quantitative Analysis	
			Rating (0-5)	Weighted rating
Controllability	30	Hydraulic actuators are typically controlled via electrically activated servo-valves. Control techniques for these actuators are also well established.	5	30
Mass, size, force, and speed	22	Hydraulic actuators have higher power-to-mass ratios than electrical or pneumatic actuators, but they require bulky pipes and control valves because of high working pressures. Since a teatcup and its pipes have a relatively low mass, the robot arm falls in the low power category - such that the actuators can easily be dimensioned to deliver the required force (or torque) and speed, and still be within suitable mass and size limits.	4	18
Environmental compatibility	28	Although a hydraulic actuator is robust and washable, it is a collector of dirt - because these actuators tend to leak, due to the high operating pressures. Therefore these actuators do not comply with the hygiene requirements of a dairying set-up.	1	6
Availability of energy source	20	The provision of hydraulic power for the actuators of a milking robot will require a special hydraulic pump - since hydraulic power is not commonly used in a dairy. Reticulation of hydraulic power is more difficult than that of electrical power, since hydraulic fluid, a pump, a reservoir, pipes, and valves are required.	2	8
	100			62

TABLE 4.5b: Analysis of hydraulic actuators for the milking robot

1	2	3	4	5
Performance parameter	Weight [%]	Qualitative Analysis of Pneumatic Actuators for a Milking Robot	Quantitative Analysis	
			Rating (0-5)	Weighted rating
Controllability	30	Pneumatic actuators are typically controlled via electrically activated servo-valves. Control techniques for these actuators are also well established. Due to the compressibility of air, pneumatic actuators are however rather sluggish, and therefore have a less rigid control action than the other two types of actuators. (Refer to a similar comment by ROSSING (1989) regarding the pneumatically actuated robot arm described by MARCHANT et al (1987).)	3	18
Mass, size, force, and speed	22	Pneumatic actuators have lower power-to-mass ratios than hydraulic actuators. The valves and pipes for a pneumatic actuator are also bulkier than the cables and switchgear required for electrical actuators. Since a teatcup and its pipes have a relatively low mass, the robot arm falls in the low power category - such that the actuators can easily be dimensioned to deliver the required force (or torque) and speed, and still be within suitable mass and size limits.	3	13
Environmental compatibility	28	Pneumatic actuators are robust; inherently clean and hygienic; and washable.	5	28
Availability of energy source	20	The provision of pneumatic power for the actuators of a milking robot will require a special air compressor - since pneumatic power is not commonly used in a dairy. The reticulation of pneumatic power is easier than that of hydraulic power, but more difficult than that of electrical power. Negative supply pressure (vacuum) is available in a dairy, because milking machines make use of vacuum to extract milk from a cow's udder. A milking machine's typical vacuum level (in the order of 50 kPa - BEZUIDENHOUT (1988)) is however too low to be used effectively for standard commercial pneumatic actuators (which typically have a nominal operating pressure of 600 kPa - FESTO (1989).)	3	12
	100			71

TABLE 4.5c: Analysis of pneumatic actuators for the milking robot

4.3.2 TYPE OF ELECTRICAL ACTUATOR

4.3.2.1 DIFFERENT ELECTRICAL ACTUATORS

4.3.2.1.1 Direct current servo motors

Direct current (DC) servo motors are commonly used for control system applications; and the theory on the control of these machines is well established. DC machines are commercially available with a wide range of supply voltages, torques, and speeds. (Small DC servo motors are currently more easily available than small AC servo motors. This should however change in future, because of rapid developments in AC drive technology.)

With a DC servo motor, speed is proportional to armature voltage, and torque is proportional to armature current. These machines can thus be used for torque-, position-, or speed control applications. Controllers for these parameters are relatively easy to construct, and are also readily available commercially.

Permanent magnet DC machines are used in low power applications, while machines with field excitation are used for larger applications. (Refer to FITZGERALD et al (1971); and SAY & TAYLOR (1980) for more detailed discussions on DC motors.)

4.3.2.1.2 Alternating current servo motors

Up to about fifteen years ago, alternating current (AC) servo motors were considered as high-speed low-torque devices, which had to be geared down if slow moving loads were to be driven. The machines were more suitable for constant speed applications, than for speed- or position control applications. (Refer to SAY (1976, p.496) and to FITZGERALD et al (1971, pp.557-564).)

More recent developments in the field of controllable AC motor drives have however made it possible to use AC motors for the abovementioned applications. AC machines are simple and robust, and its typical rotor inertia is lower than that of a similarly rated direct current (DC) machine (because of the former's simpler rotor construction). For these reasons AC motors are becoming more and more popular for robotic applications.

4.3.2.1.3 Stepper motors

The shaft position of a stepper motor can be accurately controlled through pulse sequences - generated by means of digital electronic circuits. The number of steps per revolution (i.e. the motor's positioning resolution, and its smoothness of motion) is determined by the construction of the motor. By suitably timing the pulse train, the motor output can be in the form of constant or variable torque, or speed, or acceleration. In certain cases a gearbox forms an integral part of the machine, in order to ascertain a specific number of steps per revolution, or a specific output torque.

SAY & TAYLOR (1980, pp.297-304,332-334); FITZGERALD et al (1971, pp.565-568); HAASBROEK (1985); SAY (1976, pp.498-499); and SMIT (1985) discuss the principles of stepper motors in more detail.

4.3.2.2 ACTUATOR REQUIREMENTS, AND ANALYSIS OF THE CONCEPTS IN TERMS OF THE REQUIREMENTS

In this section, the technical requirements which must be satisfied by the actuators of a milking robot, are revisited (refer to Section 4.3.1.1 above). The different electrical actuator concepts are evaluated in terms of these requirements.

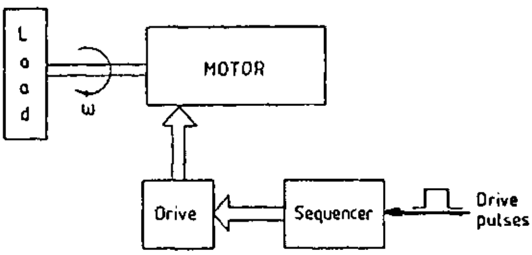
4.3.2.2.1 Controllability of the actuators

Modelling and control techniques for DC servo motors are well established, and relatively simple. (Refer to SHINNERS (1979, pp.111-119) for example.)

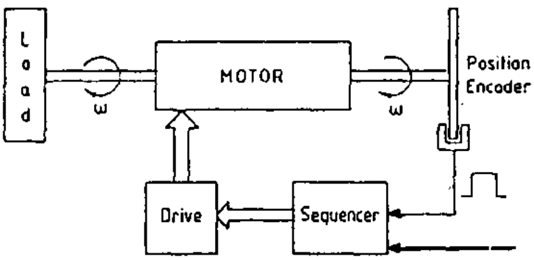
Modelling and control techniques for AC servo motors are catching up with that for DC machines. (Refer to ESSER & SKUDELNY (1991) and to MITTAL & AHMED (1983) for examples.) As pointed out by SHINNERS (1979, p.120), an AC servo motor's torque and speed are not related by a set of linear differential equations. Although linearization can be used, this aspect somehow complicates the modelling and control of these machines.

Due to the high angular accuracies of stepper motors, these machines can be used in open-loop control systems - i.e. no need for position feedback sensors (refer to Figure 4.8a).

If high slewing rates are however required (implying possible overshoot of the machine), closed-loop control becomes necessary (refer to Figure 4.8b). Modelling and control techniques for stepper motors are well established, and relatively simple. (Refer to CLARKSON & ACARNLEY (1988) for example.)



(a) Open-loop control



(b) Closed-loop control

FIGURE 4.8: Open-loop and closed-loop control of stepper motors

4.3.2.2.2 Mass, size, force, and speed of actuators

An AC motor is nominally smaller than a stepper motor, which in turn is smaller than a similarly rated permanent magnet DC motor. (Refer to FITZGERALD et al (1971, pp.559 & 568).) Brushless DC servo motors are smaller than their permanent magnet counterparts. There are however not orders of magnitude differences in mass and size between the three machine types.

All three types of electrical actuators are commercially available with a wide range of torque (or force) and speed characteristics. These characteristics can also be transformed by means of gearboxes which can be bought as part of the actuators.

4.3.2.2.3 Environmental compatibility, robustness, hygiene, and washability

All three the electrical actuator types are inherently clean and hygienic. All three types of machines can be sealed, making them washable, and dust proof. Therefore, all three types of electrical actuators can meet the environmental compatibility, robustness, hygiene, and washability requirements.

4.3.2.2.4 Availability of the required energy source

A DC servo motor requires a variable voltage (typically the armature voltage is controlled - refer to SHINNERS (1979, pp.111-116)). DC motor drives typically make use of semiconductor switching bridges to convert an AC input with fixed amplitude and frequency to a variable DC output - based on a control signal. (Refer to GOUWS (1985) for a review of these techniques; and for literature references on the subject.)

An induction motor (AC machine) requires a voltage with variable frequency as its input. Such an input is relatively easy to generate by means of an AC-to-AC converter, of which the output frequency is proportional to an input control signal - e.g. ESSER & SKUDELNY (1991).

The pulse sequence for a stepper motor can be generated by means of a digital computer, or by means of a dedicated logic circuit. A power amplifier is then used between the pulse sequence and the motor.

Electricity is an easily manipulated energy source; and since it is presumed that electricity is available in any modern dairying environment, the availability of the required energy source poses no problem for any of the three types of electrical actuators.

4.3.2.3 CHOICE OF A SUITABLE TYPE OF ELECTRICAL ACTUATOR

From the discussion of the actuator requirements in Section 4.3.2.2, it is concluded that there is not much difference in the suitability of the three types of electrical actuators. The final choice between the three actuators will not so much depend on the technical factors, as discussed in Section 4.3.2.2, but rather on personal experience and preference of the designer, on cost, and on availability.

Based on the author's personal experience with DC servo motors (refer to GOUWS (1985)), these are chosen to be used as part of the milking robot's manipulator subsystem.

4.3.3 COUPLING BETWEEN ACTUATORS AND ARM SEGMENTS

The common electrical actuators are rotating devices. The segments of the cartesian arm move linearly however. Therefore the actuators must be mounted such that its rotational quantities (angular displacement, torque, etc.) are transformed to linear quantities (translational displacement, force, etc.).

Three possible mechanisms for the coupling between the actuators and the arm segments, are investigated. The main performance parameters for these concepts are *environmental compatibility*, *controllability*, and *mass and size*; and the three concepts are discussed in terms of these parameters, below:

a. Rack and pinion. For the rack and pinion mechanism, a linear gear is mounted over the full length of the arm segment. This gear (rack) is then driven by means of a pinion on the actuator's shaft. This concept will however be influenced by dirt between the gear teeth; and it requires lubrication (e.g. grease), which prevent it from meeting the hygiene requirements of the milking robot. The gears also have inherent backlash, which can introduce system oscillations (*limit cycles* - e.g. SHINNERS (1979, p.397)) and steady-state errors. This concept will have a relatively high mass because of the gear mounted over the full length of the arm segment.

b. A worm gear has very similar characteristics than the rack and pinion concept.

c. A pulley and cable, where a thin cable is attached to two lugs on the arm's endpoints. The cable then makes one or more loops around a pulley, on the actuator's shaft. (Refer to Figure 4.9.) This concept will not be influenced by dirt; nor does it require lubrication. Provided that the coefficient of friction between the cable and the pulley is high (so that no slip occurs), and provided that the cable has a high stiffness (so that no stretching occurs), the cable mechanism has no backlash. The cable mechanism has a low mass.

From the above discussion of the three coupling concepts, the pulley and cable mechanism satisfies all the requirements; while the other two fail almost all the requirements. Therefore the cable and pulley is chosen without further analysis.

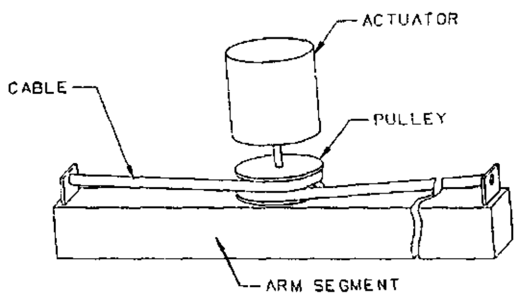


FIGURE 4.9: Pulley and cable mechanism for coupling actuators with arm segments

4.3.4 CONNECTION BETWEEN THE ELECTRICAL SUPPLY AND THE ACTUATORS

Three possible mechanisms for connecting the actuators to the electrical supply are investigated. The main performance parameter for these concepts is *environmental compatibility*; and the three concepts are discussed in terms of this parameter, below:

a. Flexible coil spring-like power cables. This concept makes use of flexible coil spring-like cables, running inside each of the hollow arm segments, to terminal blocks on the actuators. This concept requires that one side of each arm segment must be slotted over the segment's full travel length, in order that the cable can go into the bearing block, and to the actuator. This concept allows for good sealing (e.g. by means of silicon rubber) where the electrical cable passes through the bearing block's wall. Where the cable runs through the slotted arm segment, a protective bead-like bearing must be fitted around the cable, to ensure the concept's robustness. (Although slotted arm segments influence the static characteristics of the robot arm, this poses no serious problem - as indicated in Appendix F.)

b. Electrical cable on a spring-loaded reel on the bearing block. This concept provides for electrical cables on spring-loaded reels, mounted next to the actuators, on the bearing blocks. As the arm extends, the cable rolls off, while the cable is rewound (by the reel's spring action) when the arm segment moves back again. Slip rings will have to be used for transmission of power from the rotating reels, to the actuators. The cables of this concept might easily be damaged, because they are on the outside of the arm segments. Isolating the slip rings from the environment requires special attention. The environmental compatibility of this concept is ranked much lower than that of the previous concept.

c. Electrical rails on the outside of the arm segments. This concept provides for two electrical conductor rails on opposite sides of each arm segment (over the arm segment's full travel length, but isolated from the arm segment); and for carbon brushes moving with each bearing block. This concept is the least environmentally compatible, because the power rails will be uncovered - making short circuits possible.

From the above qualitative analysis, it was decided to make use of flexible coil spring-like cables, running within the slotted arm segments, for connecting the actuators to the electrical power supply.

4.3.5 DESIGN OF THE ACTUATORS FOR THE ROBOT ARM

4.3.5.1 IMPORTANT DESIGN CONSIDERATIONS

In Sections 4.3.1 to 4.3.4 it was decided that the actuator mechanism for the milking robot will have the following high level characteristics:

a. Electrical actuators will be used - more specifically, DC servo motors.

b. The actuators will be sealed in order to protect them from environmental conditions such as water and dirt. In order to aid the sealing, the actuator's shaft will go through a sealed bearing in the bearing block's wall.

c. A pulley and cable mechanism will be used to convert the actuators' rotary movement to linear movement for arm segments. (Refer to Figure 4.9 for the detail of the proposed mechanism.)

d. The electrical connections between the power supply and the actuators will be by means of a flexible coil spring-like cable. (Where the electrical cable enters the bearing block's wall, it will be sealed with silicon rubber; and where it goes through the slot in the arm segment's wall, it will have a protective bead-like bearing.)

e. The y-axis and z-axis actuators will be mounted as shown in Figure 4.7 in order to minimize the installation space required by the robot arm.

4.3.5.2 ACTUATOR RATINGS

Section F.3 in Appendix F contains the detailed design of suitable actuators for the robot arm. Different DC servo motors were analyzed, as well as different gear ratios (for speed reduction, and for increasing the load torque). From the analysis it was concluded that an *Inland RBE-00501* DC servo motor, with a 10:1 reduction gearbox, and driving the arm segment through a cable and a pulley with radius of 20 mm, would be sufficient for the z-axis. Since the x- and the y-axis have lower load masses than the z-axis, the same type of actuator will also be sufficient for these axes.

The results obtained for the *Inland RBE-00501* DC servo motor, driving the load through a gear ratio of n = 0,1 (i.e. a 10:1 reduction of motor speed), were:

a. Required motor top speed (from equation (F.47)): $N_{req} \approx 4775$ rpm (4.13)

b. Available motor top speed (from data sheet): $N_{avail} = 4951$ rpm (4.14)

c. Required motor torque (from equation (F.46)): $T_{req} \approx 0{,}029$ Nm (4.15)

d. Available motor torque (from data sheet): $T_{avail} = 0{,}033$ Nm (4.16)

4.3.6 DC POWER SUPPLY AND POWER AMPLIFIERS FOR THE ACTUATORS

In order to implement position control on the arm, the rotational positions of the arm's three actuators must be controlled individually. One way of controlling a DC motor's speed is to control its armature voltage by means of a controllable power amplifier. The motor's angular position can then be controlled by means of a position feedback loop around the power amplifier. A controllable power amplifier is typically implemented by means of a power transistor or thyristor circuit. (Refer to *Direct Current Machine Drives* in Appendix G for references on this subject.)

Commercially there is a wide variety of controllable DC motor drives available. The Inland DC motor series (chosen in Appendix F) can be provided with controlled power amplifiers, which can be used not only for armature voltage (speed and position) control, but also for armature current (torque) control.

4.4 THE ROBOT HAND

By watching experienced human milkers while attaching milking machines to cows; and also by attaching milking machines to 20 cows (refer to Section 3.4.2 for details of the experiment), it was concluded that with misalignments in the order of 45° between the centreline of a teat, and that of the teatcup, the teat was normally sucked into the teatcup, when the teatcup was moved upwards. In some rare cases, with a large angle between the teatcup and the teat, it was found that the teat would fold when the teatcup moved over it. In an automated system, the measured milk flow rate from each teat will indicate that a specific teat has folded or not. To rectify such a problem, the teatcup must be removed from the teat, and then re-attached. (Teatcups with wider-than-normal openings - refer to Section 2.4.2 - will be less inclined to cause teat folding.)

From the above it is concluded that there is no need for a robot hand with pitch (bend), roll (swivel), or yaw movement (refer to Figure 4.10); but only for a hand which can grasp a teatcup, hold it vertically, and let go of it.

4.4.1 TYPE OF ROBOT HAND

4.4.1.1 TECHNICAL PERFORMANCE REQUIREMENTS FOR THE HAND

In this section, the most important technical requirements which determine the suitability of a specific hand for a milking robot, are identified and discussed. Different hand types are then later evaluated against these parameters, in order to make a choice between them.

4.4.1.1.1 Definition of performance requirements

a. Grasping and holding capability. The most important functions of a milking robot's hand are to grasp, hold, and let go again of a milking machine's teatcup. This must be done without damaging or dropping the teatcup.

b. Reaction time. Since the milking robot is a real-time device, the reaction time of the robot hand must be short - i.e. the hand must grasp and let go at a fast rate. The rate of opening and closing of a robot hand with fingers depends on the actuators used for the hand, and on the characteristics of the transmission system (e.g. the gear ratios used).

c. Complexity of control. The positioning of the hand relative to the teatcup - when the manipulator fetches the teatcup from the retainer module (refer to Section 4.5.1) - is part of the controller's function.

d. Availability of an energy source. The hand with fingers can make use of different actuator types (electrical, hydraulic, or pneumatic). Electrical actuators were however already chosen for the robot arm, in Section 4.3 above.

e. Robustness and environmental compatibility. The hand must be able to withstand water, dust, and dirt - which typically occur in a dairying environment.

4.4.1.1.2 Weighting of performance requirements

In Table 4.6, the different robot hand performance requirements are compared with each other, in order to determine their relative importance (*weight*).

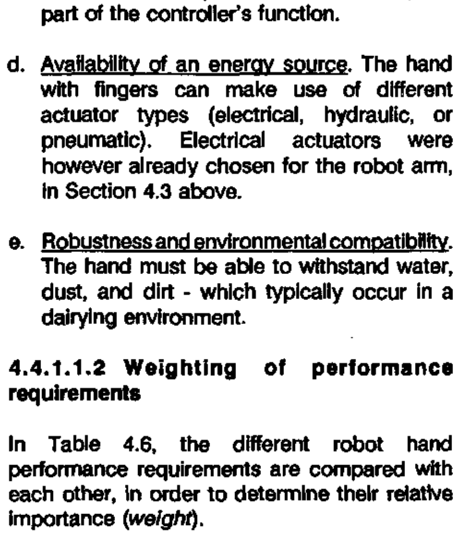


FIGURE 4.10: The three degrees of freedom of a general robot hand's wrist

	Grasping and holding capability	Reaction time	Controllability	Availability of energy source	Robustness and environmental compatibility
Grasping and holding capability	-	3	4	3	5
Reaction time	7	-	6	5	6
Controllability	6	4	-	4	5
Availability of energy source	7	5	6	-	7
Robustness and environmental compatibility	5	4	5	3	-
Sum of components	25	16	21	15	23
Weight (%)	25	16	21	15	23

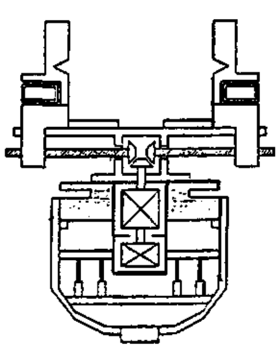
TABLE 4.6: Determination of relative weights for the trade-off between the types of robot hand

4.4.1.2 IDENTIFICATION OF HAND CONCEPTS

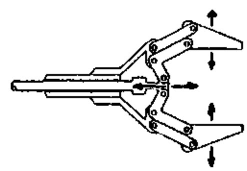
In this section, two possible **robot hand types**, namely a *hand with fingers* (Figure 4.11), and a *hand with vacuum suction cups* (Figure 4.12) are discussed. The most important technical requirements which determine the suitability of a specific hand for a milking robot, are also identified and discussed. The two hand types are then evaluated against these parameters, in order to make a choice between them.

4.4.1.2.1 Robot hand with fingers

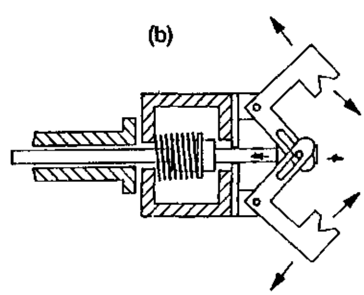
Since a teatcup is a simple cylindrical structure, two fingers (such as a human's thumb and forefinger) are sufficient to handle a teatcup. Different examples of robot hands with fingers are shown in Figure 4.11.



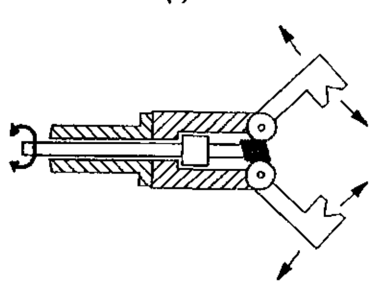
(a)



(b)



(c)



(d)

FIGURE 4.11: Examples of robot hands with fingers

4.4.1.2.2 Robot hand with vacuum suction cups

Instead of moving fingers, an "octopus-like hand" with vacuum suction cups, could possibly be used for the grasping and holding of a teatcup. Figure 4.12 illustrates the principle of such a hand.

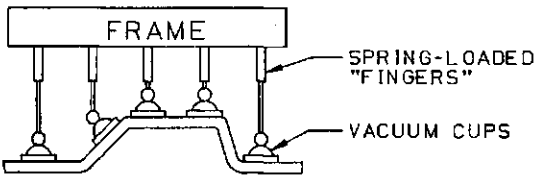


FIGURE 4.12: <u>Robot hand with vacuum cups</u>

4.4.1.3 <u>ANALYSIS OF THE ROBOT HANDS</u>

Table 4.7 represents an analysis of the two robot hand concepts - based on the defined performance parameters.

4.4.1.4 <u>CONCLUSIONS FROM THE ROBOT HAND ANALYSIS</u>

From the trade-off results in Table 4.7, it is concluded that the **robot hand with fingers** is more suitable than a hand with vacuum cups, to satisfy the specific requirements which were discussed in Section 4.4.1.1, for a milking robot.

4.4.2 CONFIGURATION OF FINGERS

In this section, two possible **robot finger configurations** are discussed in terms of its most important function, namely *grasping and holding the teatcup*. Since electrical actuators were chosen in Section 4.3 above, and since the commonly available electrical actuators are rotating devices, only rotary actuators are considered further for the robot hand. (Some of the hand configurations shown in Figure 4.11 are linearly actuated, but a rotating actuator and a rotation-to-linear converter can be used in such cases.)

a. <u>Parallel moving fingers</u> (Figures 4.11a & b). Two parallel moving fingers should be able to grasp and hold a teatcup without problems.

b. <u>Scissor-action fingers</u> (Figures 4.11c & d). Grasping a teatcup with two simple scissor-action fingers, is like attempting to cut a hard object with scissors: the object (teatcup) will slip outwards (towards to tip of the scissors). This can however be prevented by constructing the fingertips to enclose the teatcup - refer to Figure 4.11c & d.

Technically there should be very little difference between the two finger configurations. The final choice will therefore not so much depend on technical factors, but rather on personal experience or preference of the designer.

Based on the author's personal preference, scissor-action fingers are chosen to be used as part of the milking robot's manipulator subsystem.

4.4.3 TYPE OF FINGERS

In this section, two possible **types of robot fingers**, are discussed and evaluated; and a choice is made.

a. <u>Fingers adapted to the mechanical construction of the teatcup to effect grasping and holding</u>. In this case the fingers must grab the teatcup below the pulse tube, or just below the mouthpiece - refer to Figure 4.13a. Alternatively, the teatcup can be constructed to have a groove where the fingers can grab it - refer to Figure 4.13b - similar to a computer plotter grabbing its pen. This type of finger will have an inherent good holding capability; and will be robust and environmentally compatible. Force control on the fingers is not required for this type of fingers, since the fingers and the teatcup are matched.

1	2	3	4	5
Performance parameter	Weight [%]	Qualitative Analysis of a Robot Hand with Fingers for a Milking Robot	Quantitative Analysis	
			Rating (0-5)	Weighted rating
Grasping and holding capability	25	The hand with fingers will perform effective grasping and holding, provided that the hand is positioned such that there is one finger on each side of the teatcup, before the hand closes.	5	25
Reaction time	16	The robot hand with vacuum cups will have a faster action than a hand with fingers, since the former has no moving parts, but can grasp the teatcup as soon as the vacuum cups seal onto the teatcup.	3	10
Controllability	21	With moving fingers, some tolerance in the position control of the hand relative to the teatcup is allowed. Therefore the positioning of a hand with fingers is not very complex.	4	17
Availability of energy source	15	Since electricity forms part of the infrastructure of a modern dairying set-up, the availability of a suitable energy source for the hand with fingers poses no problem.	5	15
Robustness and environmental compatibility	23	Provided that open and fine gear drives (which can be blocked by dirt), are not used for the hand with fingers; and that the hand's actuator is sealed to protect it from water, such a hand is robust and suitable for use in a dairying environment.	4	18
	100			85

TABLE 4.7a: Analysis of a robot hand with fingers for the milking robot

1	2	3	4	5
Performance parameter	Weight [%]	Qualitative Analysis of a Robot Hand with Vacuum Cups for a Milking Robot	Quantitative Analysis	
			Rating (0-5)	Weighted rating
Grasping and holding capability	25	The hand with vacuum suction cups must be well positioned relative to the teatcup if it is to grab the teatcup effectively. Furthermore, this type of hand requires very good sealing between the vacuum cup and the teatcup. The teatcup's surface must therefore be clean, and smooth; and the form of the vacuum cups must be well adapted to the cylindrical form of the teatcup. The holding capability of the hand with vacuum suction cups will be affected negatively by wet conditions or dirt in the stall.	3	15
Reaction time	16	The robot hand with vacuum cups will have a faster action than a hand with fingers, since the former has no moving parts, but can grasp the teatcup as soon as the vacuum cups seal onto the teatcup.	5	16
Controllability	21	A hand making use of vacuum suction cups must be positioned accurately relative to the teatcup. Therefore its positioning is more complex than that of a hand with fingers.	3	13
Availability of energy source	15	The hand with vacuum suction cups requires a vacuum source for its operation. Since vacuum (typically in the order of 50 kPa - BEZUIDENHOUT (1988)) is available for operating the milking machines, this requirement poses no problem however.	5	15
Robustness and environmental compatibility	23	The hand with vacuum cups will definitely experience problems in an environment with water, dust, and dirt, because the vacuum cups will suck these materials in - which will clog its vacuum system.	2	9
	100			68

TABLE 4.7b: Analysis of a robot hand with vacuum cups for the milking robot

b. <u>Fingers with its tips covered by a material with a high coefficient of friction, and relying on friction between the fingertips and the teatcup to effect holding</u>. Instead of utilizing the teatcup's mechanical construction to aid the grasping and holding of the teatcup, the fingertips of a robot hand can be covered by a material with a high coefficient of friction. In this case the hand only relies on friction between the teatcup and the fingers, in order to hold the teatcup. This implies that the grasping force must be kept within limits, and that the friction coefficient of the fingers must be designed to a certain value. (CUTKOSKY & KAO (1989) and JACOBSEN et al (1988) present detailed discussions on this topic - with an extensive list of literature references included by the latter.) This type of fingers will also have an inherent good holding capability; but they will be affected adversely by dirt and water in the stall, since these could reduce the friction between the fingertips and the teatcup. If the friction between the fingers and the teatcup is too low, the teatcup will slip downwards under gravity, until the pulse tube or the mouthpiece (refer to Figure 4.13a) is caught by the fingers - resulting in the same action as that of the fingers designed to only utilize the teatcup's mechanical construction for grasping and holding. The force applied by the fingers on the teatcup must be kept within limits. If the force is too small, the teatcup will be dropped, or it will slip downwards; while either the teatcup, or the fingers might be damaged if the force is too large. The required force is also influenced by the environmental conditions.

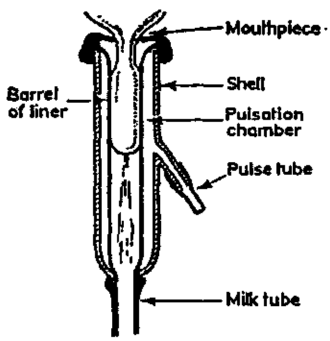
The fingers utilizing the mechanical construction of the teatcup to effect grasping and holding, requires less control, and are more robust and compatible to the dairying environment. Therefore this type of finger is considered more suitable for a milking robot's hand, than the fingers only relying on friction to hold the teatcup.

4.4.4 LOCATION OF THE ROBOT HAND'S ACTUATOR

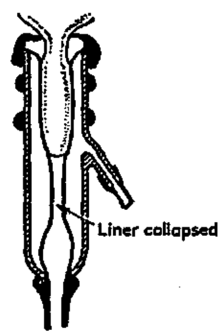
In this section two possible **actuator locations**, namely *onboard the hand*, and a *remote actuator* are briefly discussed; and a choice is made between the two concepts.

An actuator onboard the hand can either be coupled directly, or via a mechanical transmission system, to the fingers. A remote actuator can be connected to the fingers by means of mechanical links (e.g. thin cables). If cables are used as the links, such a system will only close the fingers, with a spring required to open them when the cables are released. The main advantage of a hand with a remotely located actuator is the lower mass of the hand. The main advantage of a hand with an onboard actuator is that the hand can be constructed as an autonomous unit - making the logistic support of the hand and the arm much easier. Furthermore, for a cartesian arm (as was chosen in Section 4.2.3 above), implementing suitable mechanical links between a remote actuator and the hand, will be a difficult task.

From the above qualitative analysis, a hand with an onboard actuator is chosen for the milking robot.



(a)

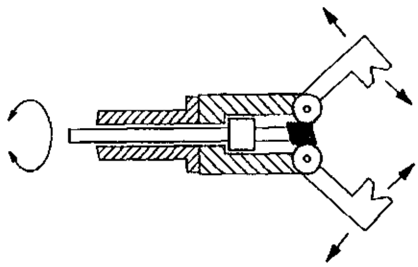


(b)

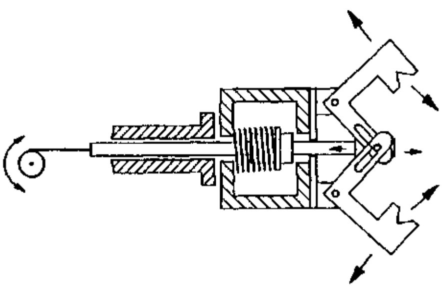
FIGURE 4.13: <u>Examples of teatcup constructions</u>

4.4.5 TYPE OF ACTUATOR ACTION

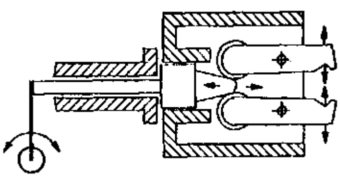
Three possible **actuator actions** are considered in this section - of which examples are shown in Figure 4.14. (Only rotating actuators are considered.)



(a) rotating actuator and screw drive



(b) rotating actuator, cable and spring



(c) rotating actuator and crank

FIGURE 4.14: Three different actuator actions for a robot hand with scissor-action fingers

4.4.5.1 DIFFERENT ACTUATOR ACTIONS

4.4.5.1.1 Rotating actuator plus screw drive

A rotating actuator plus a screw drive is shown in Figure 4.14a. The fingers are opened and closed by the actuator's movements in opposite directions. The threaded portion on the end of the actuator's extended shaft is called the worm, and the circular section on the rear end of the finger is called the gear. The movement of the gear is related to that of the worm, as expressed by equation (4.17):

$$\theta_w/\theta_g = D_g/(D_w.\tan\beta) \qquad (4.17)$$

with:-

- θ_g, θ_w: rotational position of the gear and of the worm [rad]
- D_g, D_w: diameter of the gear and of the worm [m]
- β: lead angle of the thread on the worm (the gradient of the threads on the worm, with respect to the vertical) [rad]

(The same relationship holds for the gear and worm speeds.)

The required actuator movement in order to move the tips of two worm gear actuated fingers, each with a length L_f - as shown in Figure 4.14a - a distance d_f each, is:

$$\theta_w = \theta_g.D_g/(D_w.\tan\beta)$$
$$= (d_f/L_f).D_g/(D_w.\tan\beta) \qquad (4.18)$$

4.4.5.1.2 Rotating actuator plus cable and spring

A rotating actuator plus a cable and spring mechanism is shown in Figure 4.14b. A short piece of cable is connected to the rear end of the linearly moving rod which activates the fingers. To close the fingers, the actuator winds the cable around a pulley - thus pulling the rod backwards. When the actuator direction reverses, the cable is relaxed, and the spring pushes the rod forwards - thus opening the fingers.

The required actuator movement to move the tips of two cable and spring actuated L-shaped fingers - as shown in Figure 4.14b - a distance d_f each, is calculated as follows:

$$d_f = (L_{f1}/L_{f2}).d_{lr}$$
$$= (L_{f1}/L_{f2}).\theta_{mh}.r_{ph} \qquad (4.19)$$

$$=> \quad \theta_{mh} = (L_{f2}/L_{f1}).(d_f/r_{ph}) \qquad (4.20)$$

with:-

- d_f: distance moved by each finger tip [m]
- d_{lr}: distance moved by linear actuating rod [m]
- L_{f1}: length of finger from tip to pivot point [m]
- L_{f2}: length of finger from pivot point to interaction point with actuating rod [m]

r_{ph}: radius of pulley on hand's actuator [m]

θ_{mh}: hand actuator's movement [rad]

4.4.5.1.3 Rotating actuator plus crank

An example of a rotating actuator plus a crank mechanism is shown in Figure 4.14c. The actuator shaft and the linear rod are connected by means of a short crank. The fingers are opened and closed by the actuator's movements in opposite directions. Because the endpoint of the crank on the actuator shaft follows a circular trajectory, the linearly moving rod requires space for transverse movement.

In order to move two L-shaped fingers - as shown in Figure 4.14b - a distance d_f each, by means of a crank - as shown in Figure 4.14c - the required actuator movement is:

$$d_f = (L_{f1}/L_{f2}).d_r = (L_{f1}/L_{f2}).(\sin \theta_{mh}).L_c \quad (4.21)$$

$$\Rightarrow \quad \theta_{mh} = \arcsin((L_{f2}/L_{f1}).(d_f/L_c)) \quad (4.22)$$

with L_c the crank length [m]; and the other symbols the same as those defined for equation (4.20).

4.4.5.2 EVALUATION AND CHOICE OF A SUITABLE ACTUATOR ACTION

The rotating actuator plus a screw drive (Figure 4.14a) requires lubrication on the screw drive, which can violate the hygiene requirements of a milking robot. Therefore this concept is ruled out.

The rotating actuator plus a crank mechanism (Figure 4.14c) has a nonlinear relationship between actuator rotation and finger tip movement, making its control action more complex than that of the cable and spring mechanism.

Since the rotating actuator plus a cable and spring coupling (Figure 4.14b) offers a simple and clean actuating mechanism, this concept is chosen to be implemented as part of the milking robot's hand.

4.4.6 DESIGN OF THE ROBOT HAND

4.4.6.1 FRAME OF REFERENCE FOR THE ROBOT HAND

At the beginning of Section 4.4 it was decided to implement a robot hand without the ability for pitch, roll, or yaw movement. The hand must only be able to grasp a teatcup, hold it vertically, and let go of it. The robot hand can thus be considered to be an extension of the last arm segment, and it does therefore not require its own frame of reference.

4.4.6.2 SUMMARY OF REQUIRED ROBOT HAND CONFIGURATION

In Sections 4.4.1 to 4.4.5, a robot hand with the following characteristics was chosen as the most suitable configuration to satisfy the specific requirements defined for the milking robot:

a. A robot hand with two scissor-action fingers.

b. A robot hand adapted to the teatcup's mechanical construction to effect grasping.

c. A robot hand with an onboard actuator.

d. A robot hand utilizing a rotating actuator (DC servo motor), plus a cable and spring mechanism to open and close the fingers (Figure 4.14b).

4.4.6.3 HAND CONSTRUCTION

Figure 4.15 shows a suitable hand for the milking robot - as designed in Section F.4 of Appendix F.

4.5 THE CONTROLLER

4.5.1 CONTROLLER FUNCTIONS

For each of the four teatcups, the milking robot's controller must execute the following functions:

a. Fetch the teatcup from the retainer module - which was moved in under the cow's udder by a separate control system. For the execution of this function, the controller sends out the following signals:
   i. A command to activate the hand's actuator, in order to open the fingers.
   ii. Position commands for the arm's three actuators in order to move the hand to the first teatcup in the retainer module.
   iii. A command for the hand's actuator to close the fingers, once the hand had reached the teatcup in the module.

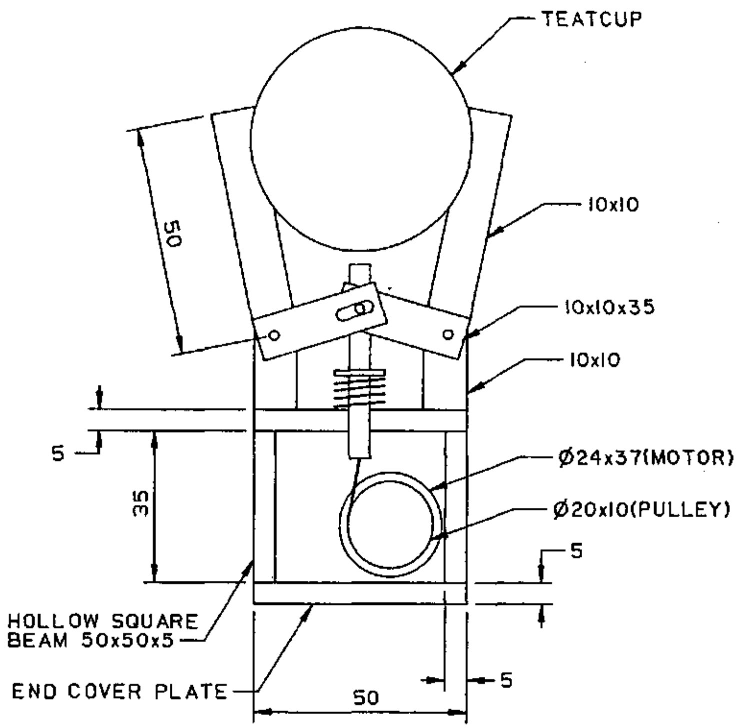


FIGURE 4.15: Proposed robot hand configuration

b. Move the teatcup from the retainer module and attach it to the appropriate teat. For the execution of this function, the controller sends out the following signals:
   i. Position commands for the arm's three actuators in order to move towards the teat, and to position the opening of the teatcup about 10 mm below the teat's endpoint. (The teat position is derived by the machine perception system, as discussed in Chapter 3.)
   ii. A position command for the arm's z-segment actuator to move upwards until the teat had been sucked in by the teatcup.

c. Release the teatcup once the teat had been correctly sucked in (which can be sensed by monitoring the milk flow). For the execution of this function, the controller sends out a command to turn the hand's actuator, in order to open the fingers.

After this last step, the process is repeated until all the teatcups have been attached. It is evident that the teatcups must be attached in a well-defined order. (The milking robot can be programmed to provide for cows which have lost one or more teats, due to mastitis for example. In such cases, teatcups will only be attached to the healthy teats; provided that an individual quarter milking machine is used - refer to Appendix D.) Once all teatcups have been attached, the robot arm returns to its base position.

A major problem will arise when the robot fails to attach one or more of the teatcups. A maximum time for attaching all the teatcups should be set, after which the attempt should be abandoned. Since cows will be milked more than twice per day by means of milking robots, it can be allowable to let a cow go unmilked once. Should the milking robot however fail to attach the milking machine to a specific cow on two consecutive occasions, an alarm indicator should alert the dairy manager via the master control system - as discussed in Section 2.4.1.

This statement strongly emphasises the view of ANSON (1983) regarding automation and automated systems: *"I think the operator will remain [...], available if needed to make critical decisions during machine operation [...]"*.

Since the controller can be located away from the robot arm (in a protected environment), there are no stringent environmental compatibility requirements to be met by the controller hardware. Therefore, the rest of this section only focuses on the control concepts; and not on the physical characteristics of the hardware.

4.5.2 CONTROL CONCEPTS

Two main questions must be answered in order to determine the control concept required for a robot arm's movements (LUH (1983)):

a. Are there obstacles in the work space ?

b. Must the robot hand follow a specified path ?

If the answer to the first question is yes, then it must be determined whether the positions of the obstacles are known beforehand, or not. The answers to these questions combine to form the six different classes of control problems as shown in Table 4.8.

Since part of a cow's udder is situated between her hind legs, there are obstacles in the work space - thus eliminating Classes 1 and 2 in Table 4.8. The positions of the cow's legs are not known exactly, which eliminates Classes 5 and 6 in Table 4.8. (Tactile or ultrasonic sensors on the hand can provide feedback to the controller in order to implement on-line obstacle avoidance travelling.) Although the robot hand is first moved in underneath the cow's body, and then moved towards the udder (as suggested by the controller functions above), it does not have to follow a unique path. Simple position control (first to the desired y-coordinate, and then to the desired x- and z-coordinates) will thus suffice. **Class 3 control can thus be used.**

		Are there obstacles in the way ?		
		No	Yes	
			Are the obstacle positions known exactly ?	
			No	Yes
Must the hand follow a specified path ?	No	<u>Class 1</u>: Position Control	<u>Class 3</u>: - Position Control - On-line obstacle avoidance travelling	<u>Class 5</u>: - Position Control - Off-line obstacle avoidance path planning
	Yes	<u>Class 2</u>: Path tracking	<u>Class 4</u>: - Path tracking - On-line obstacle avoidance travelling	<u>Class 6</u>: - Path tracking - Off-line obstacle avoidance path planning

TABLE 4.8: <u>Six classes of robot control</u>

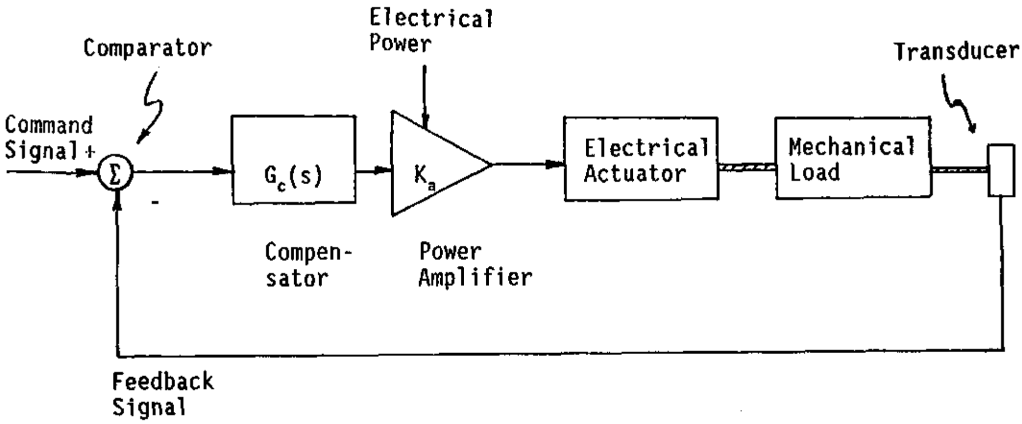


FIGURE 4.16: Generalized robot arm control system

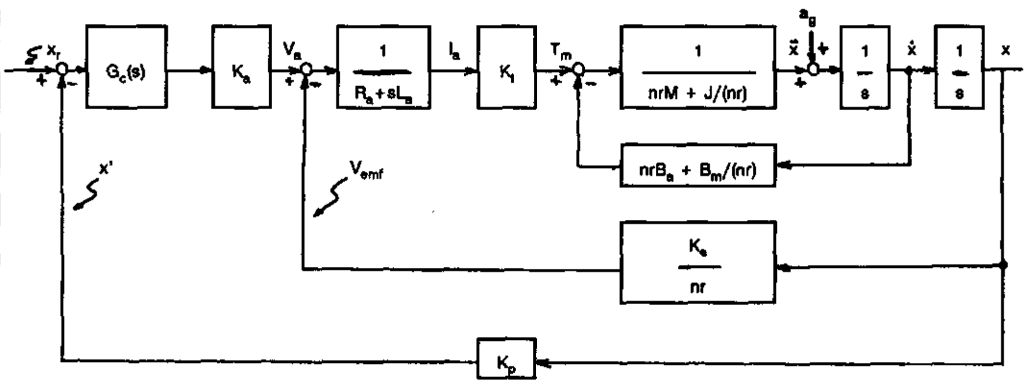


FIGURE 4.17: Generalized blockdiagram for the cartesian robot arm's three axes

4.5.3 DYNAMIC RESPONSE OF THE ROBOT ARM

Figure 4.16 shows a generalized robot arm control system; while Figure 4.17 contains a generalized blockdiagram for all three axes of the cartesian robot arm as designed in Appendix F. The parameter values are different for the three axes; while the z-axis (vertical-axis) is the only one where gravity must be added to the acceleration. (For the x- and y-arm segments $a_g = 0$ in Figure 4.17.) In Figure 4.17 the symbol x and its derivatives are used generically to indicate arm segment position, speed, and acceleration.

The open-loop transfer function, from reference position x_r to the feedback position x', for each of the three axes (in the case where the compensator $G_c(s) = 1$), is of the form shown in equation (4.23):

$$G(s) = d/[s(a.s^2 + b.s + c)] \tag{4.23}$$

with (refer to Figure 4.17):

$$a = L_a[nrM + J/(nr)]$$
$$b = R_a[nrM + J/(nr)] + L_a[nrB_a + B_m/(nr)]$$
$$c = K_tK_e/(nr) + R_a[nrB_a + B_m/(nr)]$$
$$d = K_aK_tK_p$$

and the rest of the symbols as defined in Table 4.9.

Parameter			Parameter values			Comments
Name	Description	Unit	x-axis	y-axis	z-axis	
B_a	linear viscous friction coefficient between the arm segment and the bearing block	N/(m/s)	0,001	0,001	0,001	Assumed value - based on bearing block design.
B_m	combined rotational viscous friction coefficient of the actuator and the gearbox	Nm/(rad/s)	$5{,}73.10^{-6}$	$5{,}73.10^{-6}$	$5{,}73.10^{-6}$	Total value assumed to be 1,5 times the value obtained from the data sheet for the actuator.
a_g	gravity acceleration	m/s^2	0	0	9,81	Only applicable to vertical (z) axis.
J	combined moment of inertia of the actuator, the gearbox, and the pulley	$kg.m^2$	$4{,}73.10^{-7}$	$4{,}73.10^{-7}$	$4{,}73.10^{-7}$	- Actuator plus gearbox moment of inertia assumed to be 1,5 times the value obtained from the data sheet for the actuator. - Aluminium pulley; length 10 mm; radius 20 mm.
K_a	power amplifier gain	V/V	35	35	35	Chosen as an example - true value will depend on system characteristics.
K_e	back-e.m.f. constant	V/(rad/s)	0,034	0,034	0,034	Obtained from motor data sheet.
K_t	torque constant	Nm/A	0,034	0,034	0,034	Obtained from motor data sheet.
K_p	sensitivity of the position feedback sensor	V/m	1	1	1	Chosen as an example - true value will depend on type of sensor used.
L_a	direct current motor armature inductance	H	0,0017	0,0017	0,0017	Obtained from motor data sheet.
M	total load mass experienced by the actuators	kg	4,65	7,12	8,76	Design value - Section F.3.2.2.
n	gearbox ratio (n < 1 for speed reduction)	-	0,1	0,1	0,1	Design value - Section F.3.2.3.
r	radius of the pulley on the actuator shaft	m	0,02	0,02	0,02	Design value - Section F.3.2.3.
R_a	direct current motor armature resistance	Ω	5,8	5,8	5,8	Obtained from motor data sheet.

TABLE 4.9: Parameters used for simulation of the three axes of the cartesian robot arm

4.5.3.1 STEP RESPONSE OF THE ROBOT ARM

It has already been decided that for robotic milking, a cow's movements must be restricted in the stall - by making use of mechanisms such as those mentioned in Section 2.4.1. Ideally the cow will thus stand still, and each of the three segments of the robot arm will be subjected to a step input, as the position command signal. (Some effects of slight sideways movements are considered later in Section 4.5.3.2.)

For an input with Laplace transform $X_r(s)$, the steady-state error (as defined by MARSHALL (1978, p.80)) of a specific robot axis is:

$$e_{ss} = \lim_{s \to 0} [s.X_r(s)/(1 + G_c(s).G(s))] \quad (4.24)$$

The Laplace transform of a step input with magnitude k, is $X_r(s) = k/s$, so that (4.24) reduces to (4.25) and (4.26):

$$e_{ss} = k/(1 + K_{pp}) \quad (4.25)$$

$$K_{pp} = \lim_{s \to 0} (G_c(s).G(s)) \quad (4.26)$$

In order to have a zero steady-state position error, it can be seen from (4.25) that the term K_{pp} must approach infinity - a requirement which is met if the product of transfer functions $G_c(s).G(s)$ contains a pole at $s = 0$ (i.e an integrator - $1/s$). From (4.23) and (4.26) it can be seen that this requirement will be met as long as $G_c(s)$ does not contain a loose-standing *s* in the numerator. (Refer to the list of references under *Control Systems* in Appendix G, for a more detailed discussion of steady-state errors and related topics.)

Appendix E contains the summary of a PC-MATLAB program ARMSIM.M which was written to simulate the dynamic response of the three arm segments, by making use of the blockdiagram in Figure 4.17. Table 4.9 contains the values of the parameters used in the simulations for each of the three axes (as derived in Appendix F).

Figure 4.18 contains the position responses of the three arm segments, for three different position step inputs and with $G_c(s) = 1$ (i.e. uncompensated robot arm control systems). From the results shown it is clear that all three arm segments have the desired zero steady-state error. Both the y- and the z-axis show slight overshoot, because the ratios of damping-to-mass are smaller than that for the x-axis. The y-axis overshoot is less than 0,1%; while that for the z-axis is about 1%. The overshoot of the y-axis is smaller than that of the z-axis, because the z-axis has the highest load mass - refer to Section F.3.2.2. (For the y-axis the overshoot is only evident in the 0,7 m step response - because of the resolution of the display.)

The overshoot in the responses to step inputs, of the y- and the z-arm segments, are very small. For the y-axis it is well within the tolerable manipulator error - even for the maximum step input of 0,7 m. In Section 4.5.1 above, the sequence for attaching a teatcup was described. Since the robot arm will be commanded to first move the teatcup to a position about 10 mm below the teat's endpoint, and from there to move upwards, the 1% overshoot in the z-axis is not a serious problem. (Improvement of the dynamic response is nevertheless addressed in Section 4.5.3.3 below.)

4.5.3.2 EFFECTS OF COW MOVEMENTS

Although the cow will be restricted in the stall, slight movements are still possible. An experiment was conducted in order to determine the typical moving distance and moving frequency of cows in a 900 mm wide stall, but restricted in their sideways and their fore and aft movements. The experiment involved the following:

a. Video recordings of 1 minute each were made - both from behind and from the side - of 40 cows (randomly chosen from a herd of about 300 animals) ready to be milked.

b. The recordings were played back by means of a video editing machine, with which a recording can be stepped from one image frame to the next.

c. With each recording, a measurement tape was included across the width of the stall. The images shown on the monitor could thus be calibrated in terms of distance.

d. By stepping through the image frames one by one, the distances moved by each cow from one frame to the next could be measured.

e. Since the time difference between the consecutive frames was also known, the speed of movement could be calculated.

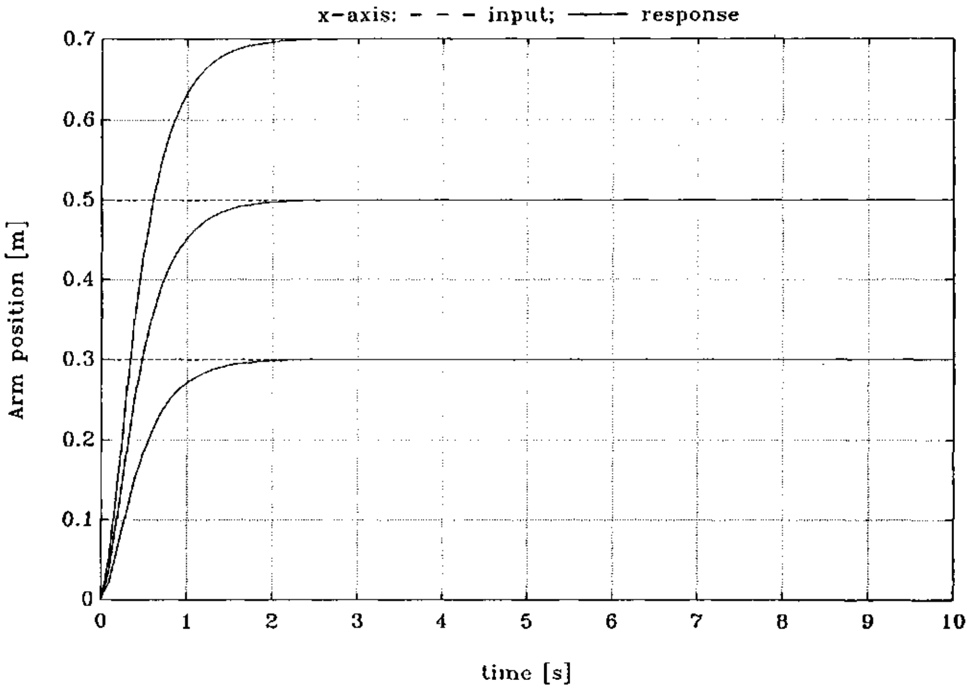


FIGURE 4.18a: Uncompensated position step response of the cartesian robot arm's x-axis

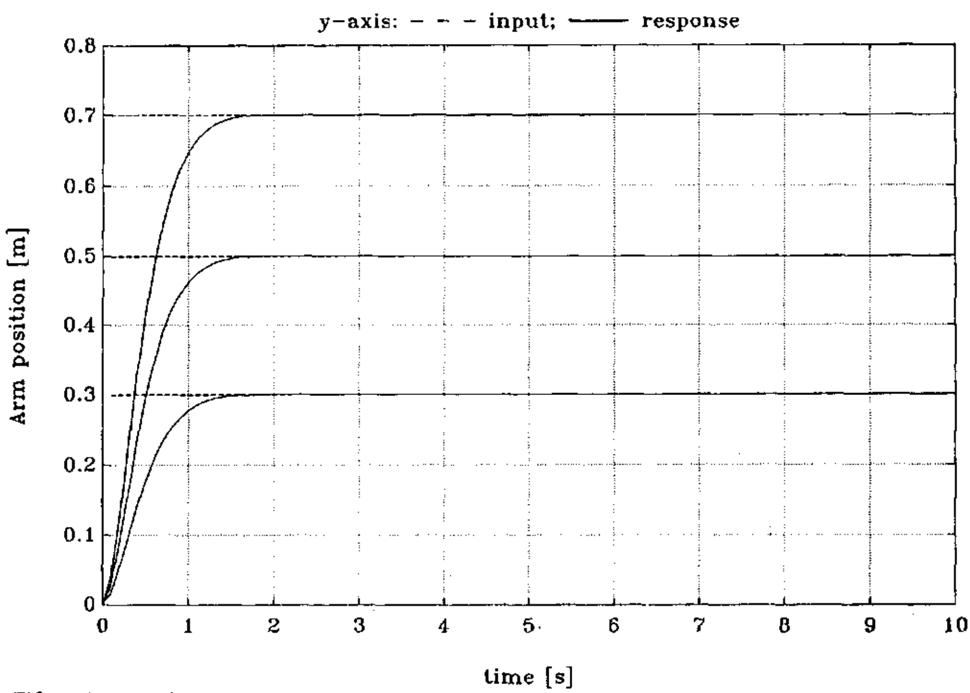


FIGURE 4.18b: Uncompensated position step response of the cartesian robot arm's y-axis

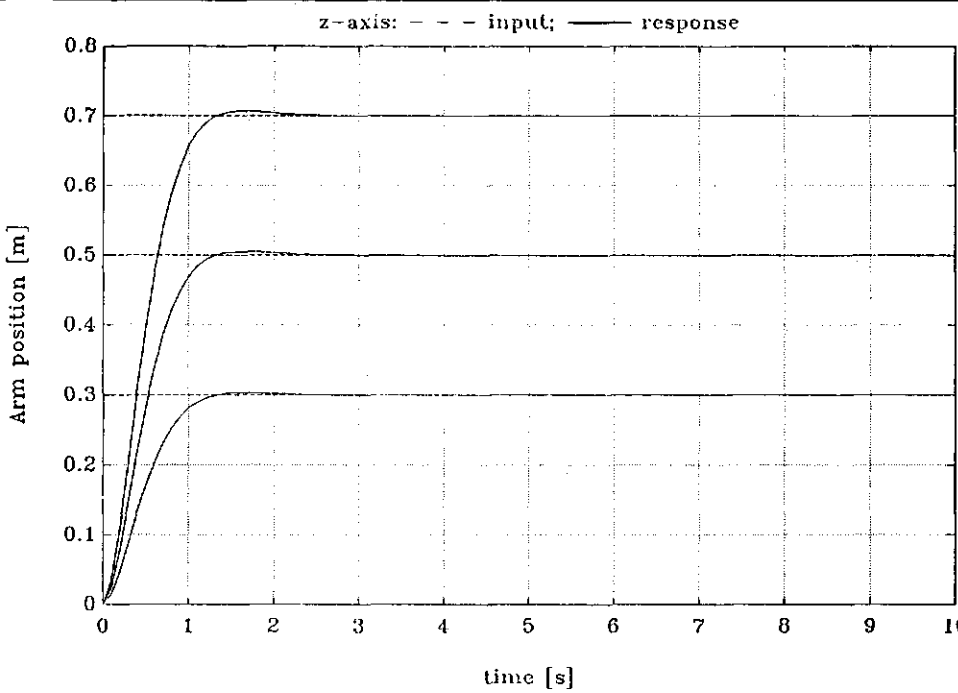


FIGURE 4.18c: Uncompensated position step response of the cartesian robot arm's z-axis

During the experiment, 9 of the 40 cows showed significant sideways movements (simple harmonic motion for limited times); only 2 cows showed significant fore and aft movements; and no cows moved significantly up and down. The following results (maximum values rounded upwards, and minimum values rounded downwards) were obtained:

a. Sideways movement:
   i. Peak distance 50 mm (i.e. 100 mm side to side), at 1 Hz maximum.
   ii. Maximum number of oscillations during one movement (i.e. before the cow stood still again): 5.
   iii. Minimum time between two consecutive "bursts" of sideways movements: 3 s.
   iv. Maximum number of "bursts" of sideways movements during the 60 s recording period: 3.

b. Fore and aft movement:
   i. Peak distance 50 mm (i.e. 100 mm side to side), at 1 Hz maximum.
   ii. Maximum number of oscillations during one movement (i.e. before the cow stood still again): 2.
   iii. Minimum time between two consecutive "bursts" of fore and aft movements: 5 s.
   iv. Maximum number of "bursts" of fore and aft movements during the 60 s recording period: 2.

(The above results apply to the cows' bodies. Since the udders are rigid before the cows are milked, these results also represent the dynamics of teat movements.)

From Figure 4.18 it is evident that the x- and the y-arm segment will reach their desired positions in well less than 5 s. If the cow would thus stand still for about 5 s, the teatcup will be attached, and sideways movements will not bother the system.

The effects of sinusoidal position commands on the x-axis (fore and aft) and the y-axis (sideways) were nevertheless investigated. The robot hand will first move towards the teatcups in the retainer rack, which had independently moved in beneath the cow. The x-, y-, and z-positions of the teatcups relative to the robot arm's reference point will be in the order of (0,6m; 0,5m; 0,2m). In order to fetch the teatcups, the three arm segments will thus be subjected to step inputs of this order; and with responses similar to that shown in Figure 4.18. Since the retainer is below the udder, the commands to move the teatcup from the retainer to the teat will be small step inputs on the three arm segments. If the cow moves during this time (and provided that the machine perception subsystem detects the movements in real-time), the position commands will be step functions with harmonic functions superimposed thereon.

The response shown in Figure 4.19 for the uncompensated y-axis is obtained under the following assumed conditions:

a. The y-coordinate of the teat relative to the position of the teatcup in the retainer, is 0,1 m. The y-arm segment is thus subjected to a 0,1 m step input (in order to move from the retainer module to the teat).

b. Before the teat is reached, the cow starts moving sideways with an amplitude of 50 mm at 1 Hz. Although the arm segment tries to follow the cow's movements, it cannot keep up.

c. After 3,5 s the cow stops moving, and the teatcup reaches the teat after another 1,5 s. Since the minimum time between two consecutive "bursts" of sideways movements was found to be 3 s, the robot should be able to attach the teatcup before the cow moves again. Even if the cow would start moving again before the teatcup is attached, it was observed that all cows familiar to the dairying environment, and who are used to being milked, eventually (within less than 60 s) stood still in the stall. Except in cases where a cow is continuously disturbed by something, or where she is unfamiliar with the environment, the milking robot should after a while be able to attach the teatcups to the teats. Even if this is not achieved at all, the cow can be allowed to exit, and come back later - refer to the discussion in Section 4.5.1 above.

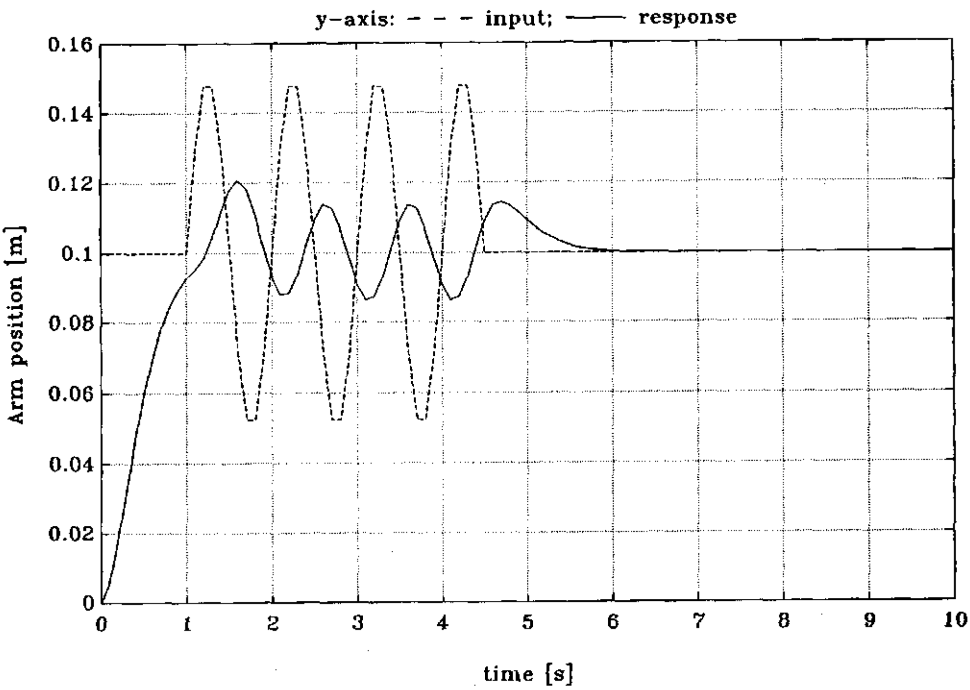


FIGURE 4.19: Uncompensated response of the y-axis to a limited-time sinusoidal input superimposed on a step input

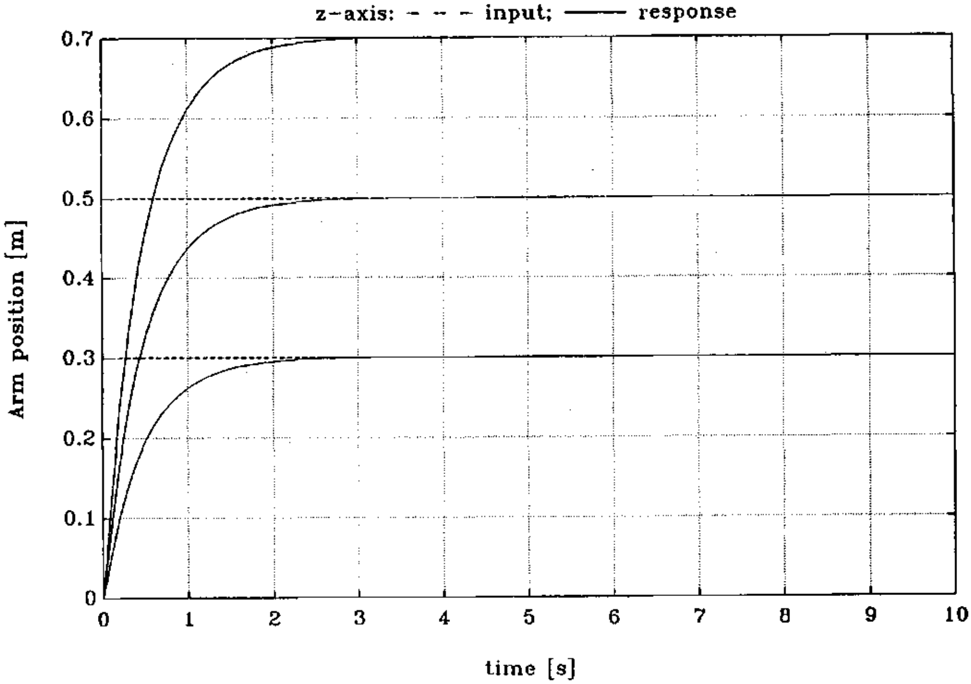


FIGURE 4.20a: <u>Compensated position step response of the cartesian robot arm's z-axis</u>

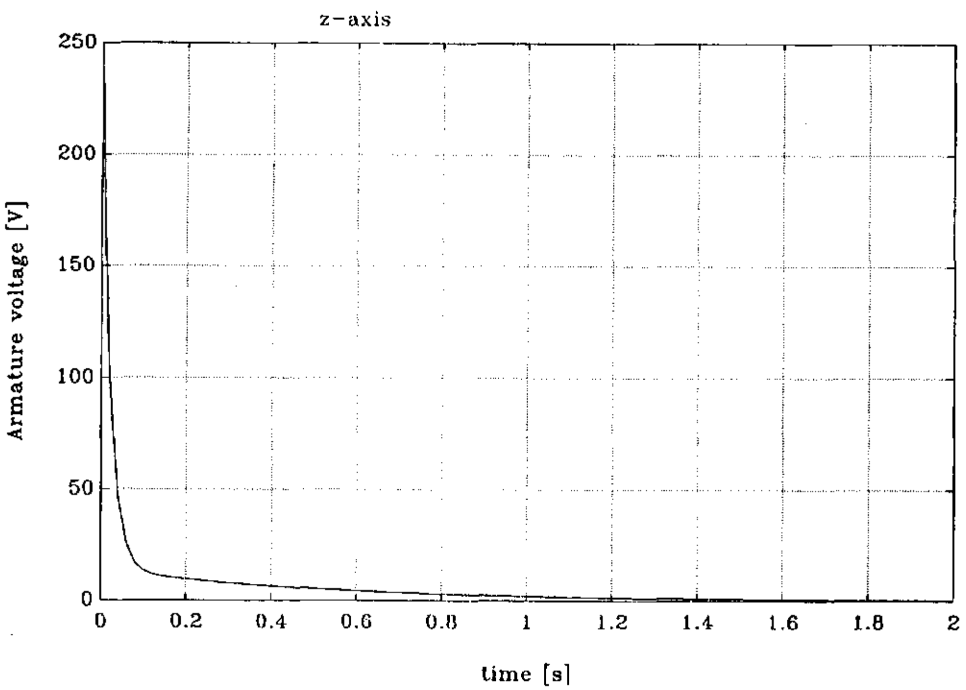


FIGURE 4.20b: <u>Armature voltage for the z-axis actuator - compensated by (4.27)</u>

4.5.3.3 IMPROVEMENT OF DYNAMIC RESPONSE

The overshoot in the responses to step inputs, of the y- *and* the z-*arm segments*, can be prevented by means of a compensator ($G_c(s)$ in Figure 4.17). Once the robot arm and -hand had been constructed, and all its parameters determined, the program ARMSIM.M and the different control system design tools of PC-MATLAB, can be used to design compensators such that the arm will have the desired dynamic response. Because a compensator is normally realized in an electronic circuit (analog compensation) or in a control algorithm (digital compensation), the overall system transfer function can be changed to virtually any form. Care must however be taken not to exceed the practical limits of the system. For example, the compensator shown in (4.27) prevents overshoot in the z-axis position, while still maintaining a reasonable response time (refer to Figure 4.20a). The compensator however requires an excessive armature voltage for the actuator at start-up (refer to Figure 4.20b). Since this voltage will be limited by the power amplifier, the system's response will be different from what was predicted theoretically.

$$G_c(s) = 10(s + 5)/(s + 50) \qquad (4.27)$$

If the system contains dominant nonlinearities - such as voltage limitation on the actuators, or dead times in the power amplifiers, or nonlinear friction for example - a simulation package such as ACSL will be required in order to predict the dynamic response. In order to design suitable compensators for such a nonlinear system, techniques such as that developed by GOUWS (1985) *will have to be used.*

4.6 CONCLUSIONS

In this chapter (and the accompanying Appendix F), the manipulator subsystem of a milking robot was analyzed and designed. The manipulator was divided into four segments - the *robot arm*; the *robot hand*; the *actuators*; and the controller.

For the robot arm, a number of **technical performance requirements** were defined and discussed. (Since the focus was on the exploration of technical ability, life cycle cost and acquisition schedule were not included.) Based on *these requirements*, a *qualitative* evaluation of four different robot arm concepts was done. This was later transformed into a more quantitative evaluation and trade-off. From the evaluation, a **cartesian robot arm** (i.e. an arm with independent movement of its *endpoint's* x-, y-, *and* z-*coordinates*), was chosen for the milking robot application. This choice was largely influenced by the simple control laws required for an arm with three decoupled degrees of freedom. Finally, a cartesian arm with reaching distances of 700 mm along each of its three axes was designed - with the constructional details presented in Appendix F.

Electrical-, hydraulic-, and pneumatic actuators were considered for the manipulator. After the definition of performance requirements, and a trade-off, electrical actuators - and more specifically **DC servo motors** - were chosen for both the arm, and the hand. In order to protect it from water and dirt, the motors will be sealed. (Appendix F contains design details regarding the actuators.)

After considering three possible mechanisms for the coupling between the actuators and the arm segments, a pulley and cable mechanism was chosen. Three possible mechanisms for connecting the electrical power supply to the actuators, were investigated, from which flexible coil spring-like cables (running inside the hollow arm segments, to *terminal blocks* on the actuators) were chosen. The cables run through slots in the arm segments - with protective bead-like bearings fitted around the cables, where they go through the slots.

After the definition of performance requirements, and different trade-offs, a robot hand with two *scissor-action fingers, adapted to the teatcup's* mechanical construction to effect grasping, with an onboard DC servo motor as actuator, and with a cable and spring mechanism to open and close the fingers, was chosen. (Appendix F contains the constructional details of a suitable hand.)

The main functions of the milking *robot's* controller were defined as: fetch the teatcup from a retainer module; move the teatcup from the retainer module and attach it to the appropriate teat; and release the teatcup once the teat had been sucked in. (After this last step, the process is repeated until all four teatcups have been attached. Once the last teatcup had been attached, the robot arm returns to its base position.) After consideration of the requirements and of the milking robot's environment, it was decided to use a **positional controller**, making use of **on-line obstacle avoidance travelling.**

Based on the design data presented in Appendix F, the robot arm was simulated by means of the PC-MATLAB program ARMSIM.M (refer to Appendix E for a summary). From this simulation the dynamic response of the arm for step inputs and for sinusoidal inputs could be predicted.

The simulation results obtained for different step-inputs indicate that all three arm segments have the desired zero steady-state error. Although the y- and the z-axis show slight overshoot, the y-axis overshoot is less than 0,1%, while that for the z-axis is about 1%. For the y-axis the overshoot is well within the tolerable manipulator error - even for the maximum step input of 0,7 m. Since the robot arm will be commanded to first move the teatcup to slightly below the teat's endpoint, and from there to move upwards, the 1% overshoot in the z-axis is not a serious problem. Although the overshoot of the y- and the z-arm segments in the responses to step inputs, can be prevented by means of a compensator, care must be taken not to exceed the practical limits of the system. As an example it was illustrated by means of simulation that the overshoot in the z-axis position can be prevented, but that the compensated system will then require an excessive armature voltage for the DC motor at start-up.

Although the cow will be restricted in the stall, slight movements are still possible. From the simulation results it was concluded that the arm segments will find it difficult to follow the cow's movements - even movements of 1 Hz frequency and peak amplitude of 50 mm. Extensive observations of cows' movements in the stall however indicated that cows familiar with the dairying environment, and who are used to being milked, usually stand still for times long enough to enable a milking robot to attach teatcups to the teats. Even if this is not achieved at all, the cow can be allowed to exit, and can be milked if she returns later. (The option of letting the cow go unmilked after she has been in the stall for a while, should however only be used when it is absolutely unavoidable. This is due to the hormone oxytocin normally being released into a cow's bloodstream - thus stimulating the let-down of her milk - as soon as she enters the familiar milking environment.)

From the analysis presented in this chapter, a suitable combination of manipulator concepts was chosen, which - when constructed as designed in this chapter and in Appendix F - will be able to attach a milking machine's teatcups to a cow's teats (provided that the teat positions were determined - in real-time - by means of the machine perception subsystem; and that the cow stands reasonably still).

The analysis presented and the conclusions reached, confirm that manipulation of a milking machine's teatcups could be effected by means of a mechanical manipulator (robot arm, robot hand, actuators, and a controller).

CHAPTER 5

SUMMARY OF RESULTS, SUGGESTIONS FOR FURTHER WORK, AND CONCLUSIONS

5.1 INTRODUCTION

The dissertation (except for the appendixes) is concluded with this chapter. A summary is presented of the results obtained, and of the most important contributions made towards the development of milking robots. A number of suggestions for further work is also made.

5.2 SUMMARY OF RESULTS OBTAINED AND CONTRIBUTIONS MADE

5.2.1 ADVANCED TECHNOLOGY IN DAIRYING

The challenges posed by the application of **advanced technology in dairying** gave rise to this research project; and it was decided to focus on **automated milking of cows**. Chapter 2 therefore commenced with a systematic identification of tasks to be performed in order to milk a cow; and an identification of the technological elements required to automate each of the tasks. From the analysis it was concluded that most of the tasks involved in the milking of a cow, are already, or can be, automated by means of existing equipment. The only tasks which are not yet automated, are those associated with attaching the milking machine's teatcups to the cow's teats. It was hypothesized that these tasks can also be automated, by means of a milking robot - consisting of a machine perception subsystem, and a manipulator subsystem.

From an evaluation of different levels of robotic development, it was concluded that third-generation robots - which are highly adaptable to its environment, because of versatile machine perception abilities - are required in order to realize the full automation of dairying. Such robots however make use of advanced equipment, and they require extensive design effort. Within the framework of the adaptability *of third-generation robots, a number of high*-level requirements could be defined; and these acted as the main drivers for the milking robot development described in this dissertation:

a. The machine perception subsystem must be able to localise a cow's teats in real-time. Limited cow movements should thus not prevent the system from operating.

b. The machine perception subsystem must not be disturbed by one or more teatcups already attached to a cow's teats - i.e. once one or more teatcups had been attached, the perception system must still be able to localise the remaining teats in real-time.

c. The manipulator subsystem must be fast enough to attach a teatcup to the teat of a cow - even if she moves around (within certain limits).

d. The teatcups must be held in a retainer rack which can move towards the cow, and from where they can be taken by the manipulator to be attached to the teats. Once milking is completed, a vacuum release system can let the teatcups drop back into the module, and the module can move out of the way again.

A number of changes to a dairying environment, which will enhance the feasibility of robotic milking, were addressed in Section 2.4. These included automated entry of the cows into the stall; handling the teatcups before the robot attaches it, and after milking; restriction of the cow's movements; and the need for an extensive information management system, to coordinate the execution of different automated dairying tasks. Changes to the construction of a milking machine - such as a milking machine with longer-than-normal pipes; and teatcups with wider-than-normal mouths - will also enhance the feasibility of robotic milking. The issue of selecting and breeding cows for easier robotic milking, was also briefly addressed.

Some important potential consequences of milking robots - including effects on milk production levels; effects on animal health; socio-economic effects; and effects on the environment - were presented in Section 2.5. Different researchers recorded increased milk production levels when milking cows more than the conventional twice per day. Since a robotic milker can increase the milking frequency, it can lead to better productivity (higher profit/cost ratio, because the same amount of milk can be produced by less cows); less animal waste to be handled (also because the same amount of milk can be produced by less cows); and lighter loads to be carried by the cows in their udders (because the cows are milked more often). Automated milking leads to less interaction between a cowman and his animals. This can lead to decreased stress levels for the animals, but it also results in a decreased human monitoring of the animals. However, an automated dairying system will ultimately form part of a computerized information management system, by which the data gathered by means of different sensors can be processed faster, more consistently, and probably continuously. Important socio-economic advantages of robotic milking can include the improvement of working conditions for farm workers (e.g. less repetitive work, with more flexible schedules); while increased agricultural productivity will have economic advantages over a wide front.

Based on a literature-survey on the state-of-the-art regarding milking robots, it is evident that there are a number of centres - mainly in Europe - where specific milking robot configurations are at different stages of research and development. (For each of these there is a main developer, in collaboration with different universities, research institutions, and companies.) Since it was not clear from the available literature which decision-criteria and concepts were considered by the different developers, it was decided to systematically address these issues in this research project. The milking robot configuration presented in this dissertation is therefore unique in the sense that it is based on a **systematic definition of performance requirements**; a **systematic identification, analysis, and trade-off of concepts**; and **research and development regarding the chosen concepts**.

The main contributions made in Chapter 2 towards the development of milking robots, are:

a. The tasks required to extract milk from a cow were systematically identified and allocated to available automation equipment. From this analysis, the full automation of the milking process was conceptualized; and those aspects requiring further research were identified.

b. From the analysis in Chapter 2 it was concluded that the development of an automatic system for attaching a milking machine to a cow's teats, was the main focus point in order to realize fully automated milking. Following this conclusion, a milking robot was defined to consist of a **machine perception subsystem**, and a **manipulator subsystem**. Such a breakdown is an essential first step for later analysis and synthesis of a suitable robotic system. (This represents the first step of the *analytical approach* described in Section 1.5.)

c. The most important consequences of robotic milking were identified - including changes required to conventional milking set-ups, advantages, and possible problem areas. This investigation highlighted important aspects of a milking robot in its intended environment - which is essential in terms of the *systems approach* described in Section 1.5.

5.2.2 MACHINE PERCEPTION FOR A MILKING ROBOT

In Chapter 3, different concepts for the machine perception subsystem of a milking robot were investigated, and some concepts were verified experimentally. The machine perception subsystem was divided into two segments, namely the sensors; and the signal processor.

The most important **technical performance requirements** (based on the author's own experience in the fields of system design and dairying) to be met by a milking robot's machine perception subsystem were defined as: *recognition of objects*; *localisation of objects*; *inspection of objects*; *sensor simplicity*; *environmental compatibility*; *sensing speed*; and *interfacing*. (Note that life cycle cost and acquisition schedule were not included in this discussion, since the focus was on the **exploration of technical ability** - a decision motivated in Section 2.6.)

Six different sensor concepts were analyzed (a television camera; an array of light beams; an ultrasonic sensor; a tactile sensor; an infrared sensor; and miniature radar and lidar). By comparing the abilities of the different sensor concepts with the requirements (by means of a formalised trade-off process), it was concluded that one or more **television cameras** should be the most suitable sensor concept to satisfy the defined technical performance requirements.

Since machine vision (i.e. a television camera as the main sensor) was the chosen sensor concept, only **image processing** techniques were addressed in the analysis and synthesis of the signal processor. The primary task of the milking robot's image processor was defined as deriving a computerized description of the spatial positions of the endpoints of a cow's four teats, in terms of world coordinates. This process is termed **scene description**. The inputs for the scene description process are image coordinates of the teat endpoints - as derived from one or more cameras; while the outputs are the calculated world coordinates of the teat endpoints.

Before analyzing scene description, the effects of errors in the calculated teat positions, on a milking robot's operation, were analyzed (theoretically and experimentally). From this analysis, the following important conclusions were reached:

a. A maximum difference of 10 mm between the teat position and the teatcup position (in the horizontal plane) can be used for design purposes.

b. No calculation errors resulting in the calculated position of a teat's endpoint being higher than the real position, can be tolerated.

c. The manipulator must first bring the opening of the teatcup to just below the teat's endpoint; and then it must move upwards for the teat to be sucked in by the teatcup. A *two-stage movement* is thus required between the point where the teatcup is grabbed by the robot hand, and the point where the teatcup has been attached to the teat.

After a theoretical investigation of the feasibility of two-dimensional scene description for the milking robot (i.e. viewing the teats from below, with one camera), it was concluded that this concept could work; but in practice it had been found that there was too little colour contrast between the teats and the udder of most cows. The teats could therefore not be distinguished from the udder. After many unsuccessful efforts to overcome this problem, the concept of two-dimensional scene description for the milking robot was discarded.

Three-dimensional scene description (defined as the transformation from a stereo pair of two-dimensional image coordinates of a point, to a description of the point in terms of three-dimensional world coordinates), was investigated next. The camera calibration method described by BALLARD & BROWN (1982) was chosen (because of its relative simplicity) for further analysis. This method defines twelve parameters for each camera, accounting for rotation, translation, and scaling between an object and its image. The parameters of two cameras (in a stereo-vision set-up as described in Appendix A) were determined experimentally, by making use of six objects with known world coordinates (x,y,z), and of which the image coordinates - (U_l,V_l) and (U_r,V_r) - were measured in a left and a right image.

Three possible routes were defined which can be followed in order to determine the world coordinates (x,y,z) of a point - if its image coordinates (in two images), and both cameras' parameters are known. By making use of *verification data* (measured world- and image coordinates of objects), errors of less than 7 mm between measured and calculated world coordinates were obtained with one of the calculation routes. Because this is within the design goal of errors less than 10 mm - as described above - it was concluded that three-dimensional scene description is a feasible concept to be implemented as part of a milking robot's machine vision system.

Before a cow's teats can be localised in terms of world coordinates by means of three-dimensional scene description, they must first be localised accurately in the two images of the udder - i.e. in terms of image coordinates. (Accuracy is of great importance, since it was shown that three-dimensional scene description is very sensitive for errors in the measured image coordinates of objects.) After investigating different localisation techniques, it was hypothesized that the edge enhanced images of cows' teats resembled parabolas, and that the parabolic Hough transform could be used for locating them in edge enhanced images. (The principles of edge enhancement were presented in Appendix B.) In order to test the hypothesis, the parabolic Hough transform was investigated in detail (with the theoretical aspects being addressed in Appendix C). The technique was verified experimentally by making use of the edge enhanced images of an artificial cow's teats, as well as that of real cows' teats. Although certain practical problems still exist, very good results were obtained with localising teat endpoints in terms of image coordinates, by means of the parabolic Hough transform.

Once image features have been located in two stereo images, the next problem is to ascertain that the same object is located in the two images. Many researchers in this field agree that the stereo correlation problem is the most difficult part of stereo machine vision. This question - which is especially relevant in the milking robot context, where each image contains four teats of similar appearance - was addressed by making use of two-dimensional camera models. Although the proposed stereo correlation method is computationally intensive, excellent results were obtained, and parallel processing should aid in streamlining it. It was thus concluded that this technique is feasible for implementation as part of a milking robot.

The main contributions made in Chapter 3 towards the development of milking robots, are:

a. The most important technical performance requirements which have to be met by a milking robot's machine perception subsystem, were identified and formalised.

b. A formal trade-off procedure was used for choosing between different concepts. Although this procedure cannot provide absolutely accurate answers, it ensures that different concepts are evaluated on an equal basis - against the same requirements.

c. It was shown that two-dimensional scene description by means of machine vision, was theoretically feasible, but that practical aspects hampered its implementation for the milking robot.

d. Three-dimensional scene description was thoroughly investigated, and experimentally found to be feasible. Different calculation routes for the transform from two sets of two-dimensional image coordinates, to one set of three-dimensional world coordinates were defined and investigated - from which a suitable method was chosen. (The author has not yet come across similar discussions and evaluations of such calculation routes, in the literature.)

e. The parabolic Hough transform was implemented in software, and was shown to be very suitable for localising a cow's teat endpoints in an edge enhanced image. The parabolic Hough transform is not often used, due to its computational complexity; and although its implementation as part of a milking robot still requires further research, a thorough baseline has been established through this work.

f. From early work done as part of this research, certain research needs in the field of edge enhancement techniques were identified by the author. Based on this analysis of needs, CHRISTIANSEN (1990) had performed research in this field, obtaining excellent results regarding the evaluation of edge enhancement operators.

g. A method was proposed, evaluated, and found feasible, for stereo correlation in images where the objects do not necessarily appear in the same order in the two images. With this method (which makes use of two-dimensional camera models), correlating the four teats of a cow in two images, is possible.

5.2.3 MECHANICAL MANIPULATION FOR A MILKING ROBOT

In Chapter 4 (and Appendix F), the manipulator subsystem of a milking robot was analyzed and designed. The manipulator was divided into four segments, namely the robot arm; the actuators; the robot hand; and the controller.

The most important technical performance parameters against which a milking robot's arm must be measured, were defined as *Kinematic and Dynamic Ability*; *Action Volume*; *Operating Space Required*; *Steady State Position Error*; and *Robustness and Environmental Compatibility*. (As for the machine perception subsystem, the focus was on the exploration of technical ability. Life cycle cost and acquisition schedule were thus not included as performance parameters for the robot arm.)

Four robot arm concepts were investigated: the cartesian-, the cylindrical-, the spherical-, and the articulated arm. After a qualitative analysis of each arm concept in terms of the defined performance requirements, followed by a more quantitative trade-off, it was concluded that the four arm configurations have very similar characteristics. Since the **cartesian robot arm** (*i.e. an arm with independent movement of its endpoint's x-, y-, and z-coordinates*), fared slightly better than the others in the trade-off, it was the chosen concept. A robot arm with the following mechanical characteristics was designed in Appendix F:

a. Cartesian arm, with a reaching distance of 700 mm for each arm segment.

b. Hollow aluminium beams (50 mm outer dimension, 40 mm inner dimension, and mass of 1,65 kg) for each arm segment.

c. Static errors of the robot hand's position - due to different static loads acting on arm segments: $x_e \approx 0,3$ mm; $y_e \approx 0,5$ mm; and $z_e \approx 2,3$ mm. (The static error in the x-y (or horizontal-) plane is thus less than 1 mm - which is well within tolerable limits. The vertical error (along the z-axis) causes the hand to be slightly below the teat endpoint - which is desirable, since the teatcup must first be moved to just below the teat's endpoint, before it is moved upwards. (Refer to the analysis performed in Section 3.4.2.)

Electrical-, hydraulic-, and pneumatic actuators were considered for the milking robot. The technical performance parameters against which the actuators had to be measured, were defined as *Controllability*; *Mass, Size, Force and Speed*; *Environmental Compatibility*; and *Availability of Energy Source*. After a first round trade-off, it was concluded that **electrical actuators** would best meet all the defined requirements - provided that the actuators are sealed to prevent water, dust, and dirt from entering it.

Three different types of electrical actuators were then investigated (direct current servo motors; alternating current servo motors; and stepper motors). Based on the defined actuator requirements, it was concluded that there is not much difference in the suitability of the three types of electrical actuators. Based on the *author's personal experience and preference*, DC servo motors were chosen to be used as part of the milking robot's manipulator subsystem. (From the definition of each arm segment's required reaching distance, speed, and acceleration, and by making use of each arm segment's equation of motion, suitable actuators were chosen in Appendix F - based on data in catalogues.)

From an investigation of different **coupling mechanisms between the actuators and the arm segments**, it was decided to make use of a pulley on each actuator's shaft, pulling a cable attached to the arm segment.

From an investigation of different **mechanisms for connecting the actuators to their electrical supply**, it was decided to make use of flexible coil spring-like cables, running within the arm segments. Each arm segment will be slotted in order that the cable can exit the arm segment through a bead-like sliding bearing, towards the actuator.

From observations and experimental measurements it was found that with misalignments in the order of 45° between the centreline of a teat, and that of the teatcup, teats were normally still sucked into the teatcup, when the teatcup was moved upwards. (Provision shall be made in the system's control logic to remove and re-attach a teatcup, should the system sense that the teatcup was not attached correctly to the teat.) It was therefore concluded that there was no need for a robot hand with pitch, roll, or yaw movement; but only for a hand which can grasp a teatcup, hold it vertically, and let go of it again. Two main **robot hand concepts** which satisfy these requirements were investigated, namely a robot hand with fingers, and a robot hand with vacuum suction cups.

The technical performance parameters for a robot hand were defined as *Grasping and Holding Capability*; *Reaction Time*; *Complexity of Control*; *Availability of an Energy Source*; and *Robustness and Environmental Compatibility*. From a trade-off making use of these parameters, it was concluded that a **robot hand with fingers** would best satisfy the defined requirements. Following different other trade-offs, a robot hand was designed in Appendix F, incorporating two scissor-action fingers, which utilize the mechanical construction of the teatcup to effect grasping and holding of the teatcup. It was decided to use a hand with an onboard actuator, in order to simplify construction, operation, and logistic support of the manipulator. Since a rotating actuator plus a cable and spring coupling offered a simple and clean actuating mechanism for the hand, this concept was chosen.

The main functions of the milking robot's **controller** were defined as: *fetch the teatcup from a retainer module*; *move the teatcup from the retainer module and attach it to the appropriate teat*; and *release the teatcup once the teat had been sucked in*. (After this last step, the process must be repeated until all four teatcups have been attached. Once the last teatcup had been attached, the robot arm returns to its base position. If, for some reason, all four teatcups cannot be attached correctly within a specified time, those teatcups already attached shall be allowed to drop off, and the cow must exit the stall. Another attempt to milk her can then be made when she returns to the stall later. Should the problem be recurrent, an alarm must be raised.)

Six control concepts for the milking robot were investigated, namely *positional control*; *path tracking*; *positional control with on-line obstacle avoidance travelling*; *path tracking with on-line obstacle avoidance travelling*; *positional control with off-line obstacle avoidance path planning*; and *path tracking with off-line obstacle avoidance path planning*. After consideration of the requirements, and of the milking robot's environment, it was decided to use a **positional controller**, making use of **on-line obstacle avoidance travelling**.

Finally, the three arm segments' dynamic responses to different input functions (e.g. step inputs, sinusoidal inputs, or sinusoidal inputs superimposed on step inputs) were simulated by means of a computer program. The simulation program can also be used for designing suitable compensators for the manipulator, once it had been constructed, and once all the parameters in the system's equations of motion had been determined. The simulation was used to evaluate the effects of lateral movements of the cow, on the controller and the robot arm. From this it was concluded that the cow must stand as still as possible for the robot to be effective. Mechanisms to restrict the movements of cows in the stall will thus definitely have to be implemented.

The main contributions made in Chapter 4 towards the development of milking robots, are:

a. The most important technical performance requirements which have to be met by the different segments of a milking robot's manipulator subsystem, were identified and formalised.

b. Numerous experimental measurements were made in order to determine the typical dimensions of a milking robot's operating environment; and to quantify the performance requirements.

c. A complete robotic manipulator was designed - involving the analysis and trade-off of numerous concepts for the different segments of the manipulator. A number of computer programs were also written for general purpose design and simulation of the manipulator.

d. Control laws for "pick and place robots" were analyzed and sorted into six classes. This represents an extension of similar classifications found in the literature.

e. Measurements were done in order to determine the dynamics of cow movements in the stall. Based on this data, typical dynamic responses of the designed manipulator were simulated, from which the importance of mechanisms for restricting the movements of cows in the stall, was confirmed.

5.3 SUGGESTIONS FOR FURTHER WORK

Since the research process does not only generate answers, but also new questions, a brief discussion regarding some questions which had arisen during the systematic investigation of a milking robot's subsystems, is presented in this section. These aspects require further work in order to realize the implementation of a machine vision based robotic milker.

5.3.1 MACHINE PERCEPTION

Although both the defined subsystems of a machine vision based milking robot have aspects requiring further research, it is concluded from the results presented that there are more questions unanswered for the machine perception subsystem, than for the manipulator subsystem. The most important issues are:

a. Two-dimensional scene description. In Chapter 3 it was concluded that two-dimensional scene description was not feasible for the milking robot. The main reason for this was the difficulty experienced by the machine vision system to distinguish between a cow's teats and her udder, when viewing the udder and teats from below. Because of the potential advantages of this concept (cheaper equipment; and a less complex system), it should be researched further in future.

b. Accuracy of three-dimensional scene description. In Chapter 3 it was shown that the values of scene depth calculated from two stereo images, are very sensitive for measurement errors along both axes in the two images. The placement of the two cameras relative to each other also influence the accuracy of the three-dimensional scene description process. Methods to increase the measurement accuracy of the image coordinates of objects; and methods to determine optimal camera positions will thus have to be addressed in future research. In Table 3.11 it was shown that acceptably small calculation errors were attainable by taking the average of 100 calculations in cases where the image coordinates were corrupted with random measurement errors. The use of such statistical methods for the milking robot's perception system (i.e. repeating the measurements and calculations of the teat positions a number of times, and taking the averages) should be further investigated. (Of course such methods would require even faster image processing equipment in order to satisfy the real-time localisation requirement.)

c. Faster image processing. An experimental machine vision subsystem for a milking robot was implemented by means of two television cameras as the main sensors; an image grabber card in a personal computer; and some image processing software. This set-up operates on single image frames; and it is not nearly fast enough for real-time image processing though. The answer to this problem lies in the use of parallel processors - e.g. **neural networks** or **transputers** - for image processing. (See Appendix G for relevant literature references.) Because of the need for faster image processing than that used for this research project, it can be concluded that the application of **parallel image processing** is one of the areas requiring the most research effort in order to realize a real-time machine vision system for a milking robot.

d. Automatic thresholding for edge enhancement. In order to reduce image data (without reducing image information), edge enhancement is often performed (refer to Appendix B). For this process a threshold is required, according to which a pixel is classified as belonging to an edge or not. Although some algorithms for automatic determination of the threshold are discussed in the literature (e.g. McKEE & AGGARWAL (1975); SID-AHMED (1987); and WONG & SAHOO (1989)), the best results still seem to be reached by determining the threshold manually through trial and error. This is of course unacceptable for an automated system such as a milking robot; and further research in this area is thus essential.

e. Refining the parabolic Hough transform. In Section 3.4.4 it was shown experimentally that good results are obtained by using the parabolic Hough transform to find a cow's teats in an edge enhanced image of her udder and teats. However, with the implementation of this technique in PC-MATLAB programs (HOUART.M and HOUART1.M - refer to Appendix E), only one parabola could be detected at a time in a given image. This is not an inherent limitation of the Hough transform though, since one of its features is the ability to detect multiple curves in the same image; but it is a restriction of the computer software and hardware used. In order to overcome this problem, the data management for the parabolic Hough transforms will have to be improved. This depends on the availability of more computer memory; and on a suitable threshold being used in order to classify a detected parabola as a cow's teat or not. The first problem merely depends on the eventual computer architecture; while the second problem can be solved by further research along the lines of that reported by WHITTAKER et al (1987), regarding automated thresholding for the Hough transform.

f. Artificial intelligence. The machine vision process as described in this dissertation, is a sequential (or hierarchical) process; and it is mainly based on locating pre-defined features in images. With the emergence of artificial intelligence (see Appendix G for relevant literature references) the emphasis in machine perception is shifting towards a more interactive approach, making use of continuous feedback and feed-forward between the different elements of the machine perception system, in order to adapt their functioning as new information about the scene becomes available. This enables a transition from a rigidly programmed approach, to an adaptable approach in which the image is *"understood"*, and in which logical deductions are continuously used in the processing of the image. The use of artificial intelligence for the implementation of machine perception holds many potential advantages, and can enhance the abilities of sensor-based robots. Therefore further research in this area is essential.

5.3.2 MECHANICAL MANIPULATION

In any feedback control system it is important that the controlled variable can be accurately measured, and fed back to the controller. For a milking robot, the controlled variable is the hand position - which is measured indirectly by means of sensors such as positional encoders on each arm segment's actuator, or on the arm segment itself. The robot accuracy will be influenced negatively by differences between the measured value and the real value of the hand position. Such differences can be due to effects such as bending of the arm segments or backlash.

Depending on the measurement accuracy attainable, machine vision based position measurements of a robot arm's endpoint could possibly overcome the above problem. Such a solution could also allow for a less rigid arm construction. Although functionally possible - as indicated by the results presented in Chapter 3 - such measurements will further increase the computational complexity of the machine vision system. Locating the robot hand will however be easier than locating the four teats, since a well defined point - such as a small light on the robot hand - could be tracked. Since the above approach has obvious pros and cons, it is suggested that its implications should be investigated further. (Refer to the "mixing" of teatcup position measurements shown in Figure 2.1.)

5.3.3 GENERAL ASPECTS

A cow's interaction with machines such as a feeding station, a milking machine, and a milking robot might increase her stress level. From the available literature it seems that this aspect has not yet received much research attention. Research in the field of animal-machine interfacing - possibly along the lines of existing man-machine interface studies - will be useful from an animal health point of view, as well as from an economic point of view. It is therefore suggested that this aspect should be addressed in future research.

5.4 OVERALL CONCLUSIONS

A number of practical problems still exist with the implementation of three-dimensional scene description, the parabolic Hough transform for localisation of a cow's teats in edge enhanced images, and with the use of two-dimensional camera models for stereo correlation. These techniques have however been demonstrated to possess all the basic characteristics required by the machine perception subsystem for a milking robot. Since the problem areas are not of a fundamental nature, the overall conclusion reached from the research on machine perception for a milking robot, is that three-dimensional scene description - based on the data derived from a stereo pair of television cameras - is feasible for implementation as part a milking robot.

From the research on mechanical manipulation for a milking robot, a suitable combination of manipulator concepts could be defined, which will be able to attach a milking machine's teatcups to a cow's teats - provided that the teat positions are known and that the cow stands reasonably still.

Although there are still some practical problems to be solved, the overall conclusion from the research results presented in this dissertation is that milking robots - implemented by combining *machine perception* and *mechanical manipulation* - are technically feasible. It will still be some time before such milking robots become a common reality, but it should be remembered that most successful systems are driven by technology and opportunities, and are not acquired only in reaction to existing needs.

APPENDIX A

CONFIGURATION OF AN EXPERIMENTAL MACHINE PERCEPTION SUBSYSTEM

A.1 INTRODUCTION

In this appendix the configuration of an experimental set-up, for the investigation of machine perception concepts for a milking robot, is briefly discussed. Since a **television camera** was chosen in Chapter 3 as a suitable main sensor for the machine perception subsystem of the milking robot, the focus is on **machine vision**.

A.2 EXPERIMENTAL MACHINE VISION HARDWARE

Figure A.1 shows a schematic representation of an experimental set-up for image formation; for data transfer to the image processor; and for image processing. The hardware of the experimental system consists of the following:

a. Two National WVP100N colour television cameras.

b. Two National NV-100 video cassette recorders (VCRs).

c. One TMC 210 mm monochrome video display unit.

d. One IBM PC/AT compatible personal computer (80286 micro processor, and 80287 numerical co-processor); with both colour and monochrome video display units, 640 kilobyte RAM, a 20 megabyte hard disk, and a 360 kilobyte floppy disk drive. (All operating under DOS control.)

e. One Oculus 200 frame grabber card - slotted into the computer. (Supplied by Coreco Computer Vision Products and Support, 555 St.Thomas, Longueuil, Quebec, Canada J4H 3A7.)

(Note that the choice of hardware elements was largely influenced by the availability of equipment - which was either borrowed, or bought at reasonable prices.)

The frame grabber card has an input- and an output connector on its back plate. A coaxial cable is used to connect the "video out" connector on the VCR, to "input" on the frame grabber card. The TV camera must be plugged into the VCR, and the VCR connected to the frame grabber, for the TV camera to communicate with the frame grabber card. The frame grabber card can also be used to write an image to the video monitor, which is done via a coaxial cable from the card's "output", to "video in" on the monitor.

Although two cameras (and VCRs) are used in the set-up shown in Figure A.1, only one can be connected to the frame grabber card at a time. For stereo vision experiments, two images are recorded by means of the cameras and the VCRs, and are then processed one after the other by the same image processor. For a more advanced development model, each camera will be connected to its own dedicated image processor, and the results from the two processors will be used by a third processor - for calculation of the three-dimensional positions of the teats.

A.3 EXPERIMENTAL IMAGE PROCESSING SOFTWARE

The Oculus 200 frame grabber card was obtained with a number of Turbo Pascal 3 image processing routines. Some of these routines were adapted and extended in Turbo Pascal 4, in order to suit specific requirements.

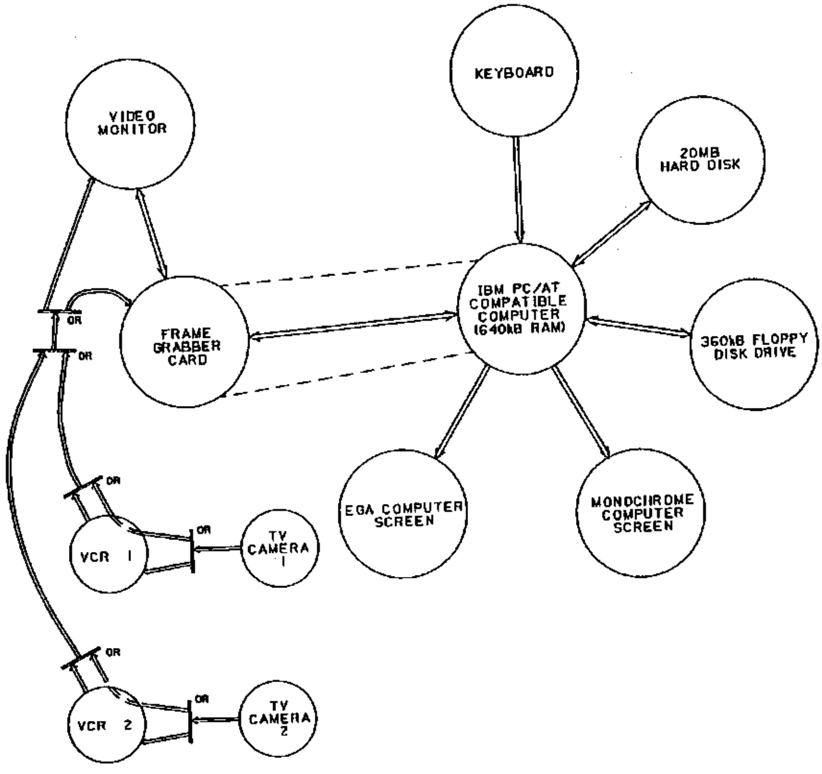


FIGURE A.1: <u>Schematic representation of an experimental machine vision system for the milking robot</u>

A.3.1 TRANSFERRING AN IMAGE TO THE DATA STORAGE UNIT

The procedure for transferring an image from the television camera (or from the video cassette recorder) to the data storage unit is the following:

a. Display the desired image on the video monitor - with the television camera in record mode (or with the video cassette recorder in play mode).

b. Run the Turbo Pascal program GRAB.PAS (refer to Appendix E), and press "G" followed by "ENTER" to grab the desired image. (The image will be frozen on the video monitor, and the camera (or the VCR) must be stopped now.)

c. Run the Turbo Pascal program VIDEOREA.PAS (Appendix E), to read the image from the video monitor, and to write it to the data storage unit.

The program VIDEOREA.PAS will ask for a filename, and it will store the image on hard disk, in sixteen blocks - with filenames *filename*1.vdi, *filename*2.vdi, ..., *filename*16.vdi. Each file will contain a block of 8 bit grey scale pixels, 32 rows by 512 columns. The file format is shown in Figure A.2.

A.3.2 TRANSFERRING AN IMAGE FROM THE DATA STORAGE UNIT FOR IMAGE PROCESSING

The Turbo Pascal program IMPROC.PAS (refer to Appendix E for a summary of the program) contains a module (*Procedure Display*) for displaying a *.vdi file on the computer screen; as well as other modules to perform a number of image processing operations - as discussed in Section 3.4 - on the image.

data block number	(first column;first row)	(last column;first row)
	(first column;last row)	(last column;last row)
1	(0;0)	(511;0)
	(0;31)	(511;31)
2	(0;32)	(511,32)
	(0;63)	(511;63)
n (3,4,....,15)	(0;[n-1]*32)	(511;[n-1]*32)
	(0;[n*32]-1)	(511;[n*32]-1)
16	(0;480)	(511;480)
	(0;511)	(511;511)

FIGURE A.2: File format for grey scale image files

A.4 COMMENTS ON MORE ADVANCED DEVELOPMENT MODELS

It must be strongly emphasised that the set-up shown in Figure A.1 is an **experimental system**, suitable for the **exploration of concepts**. This set-up however contains equipment which will be redundant in a production model of a machine vision-based milking robot; and in other areas it requires extensions of the hardware and the software.

Colour cameras are used, but the image processing only makes use of grey-scale images. Although the equipment is thus more sophisticated than what is needed, it was available at a reasonable price; and since it is completely suitable for the purpose, it was bought. For a production model milking robot, *smaller and less sophisticated cameras will* however be used. Each camera will also have a dedicated image processor (hardware and software); while a third image processor will be used for combining the results from the two cameras and their image processors.

APPENDIX B

DATA REDUCTION AND EDGE ENHANCEMENT IN IMAGES FOR THE MILKING ROBOT

B.1 INTRODUCTION

ATTNEAVE (1954) found in experiments with the human visual system, that objects could often be adequately recognised from a rough outline sketch. From this finding it was concluded that the most information about an image is contained in and around the edges of objects in the image. Object edges in an image can be detected by analyzing the changes in light intensity in the image. If only the data representing the edge points are kept, and the rest of the data discarded, marked reductions in image **data** is possible, while the **information** content changes very little.

GOUWS (1988a) conducted a literature survey, and analyzed seventeen publications on edge enhancement techniques and algorithms (CHANDA et al (1985); DELP & CHU (1985); DRESCHLER & NAGEL (1983); GEUEN (1983); GU & HUANG (1985); JACOBUS & CHIEN (1981); KUNT et al (1985); LIEDTKE (1983); LUNSCHER & BEDDOES (1986); MÉRŐ (1981); MITICHE & AGGARWAL (1983); RAMER (1975a,b); SHIPMAN et al (1984); SHIRAI & TSUJI (1972); TORRE & POGGIO (1986); VERBEEK et al (1987)). Many of the algorithms discussed in these publications are claimed to be "optimal" or "the best" - e.g. GEUEN (1983, p.492); LUNSCHER & BEDDOES (1986, p.311). Such claims are however very subjective, and the applicability of an algorithm to a specific scene, depends on a large number of factors.

From the literature survey, it was concluded that edge enhancement operators can broadly be classified as **local operators** and **regional operators** (in the spatial- or image domain); and as **frequency domain filters**.

Local operators scan the image, and operate on a small area at each scan position. The main disadvantage of a local operator is that enhanced edge pixels are "loose standing" - i.e. there is no direct relationship between the results obtained at two consecutive scan positions. These operators are relatively simple - which has a positive effect on computational speed. Being localized, these operators are also well suited for parallel processing.

Local operators typically determine spatial gradients in images. Spatial gradients (or intensity changes) in images can be detected similar to the detection of changes in algebraic functions - i.e. by differentiation. (Early examples of this technique can be found in the work of DINEEN (1955), KANAL & RANDALL (1964), and ROBERTS (1965); while later discussions are presented by BALLARD & BROWN (1982, pp.76-79); DUDA & HART (1973, pp.267-272); and NEVATIA (1982, pp.24-28).)

Regional operators act on relatively large image regions (as opposed to local operators acting on only one pixel plus its few neighbours). Regional operators typically compare image segments with pre-defined data; or use large areas in an image in order to compute the associated edge image. Regional operators are generally more complex to implement than local operators.

The third class of operator, is the frequency domain filter. In order to apply a filter to an image, the image must first be transformed from the spatial domain to the frequency domain. (Similar to the algebraic Fourier transform.)

In the first part of this appendix, different edge enhancement operators are discussed - some in more detail than others. This appendix is by no means intended to be a complete discussion of edge enhancement techniques or of all the available algorithms; but rather to make visible

data block number	(first column;first row) (first column;last row)	(last column;first row) (last column;last row)
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Local operators scan the image, and operate on a small area at each scan position. The main disadvantage of a local operator is that enhanced edge pixels are "loose standing" - i.e. there is no direct relationship between the results obtained at two consecutive scan positions. These operators are relatively simple - which has a positive effect on computational speed. Being localized, these operators are also well suited for parallel processing.

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In the first part of this appendix, different edge enhancement operators are discussed - some in more detail than others. This appendix is by no means intended to be a complete discussion of edge enhancement techniques or of all the available algorithms; but rather to make visible the most important principles, and to point out the trends in this field. For more detailed discussions, the reader is referred to the literature references cited - especially CHRISTIANSEN (1990) and NEVATIA (1982), who provide good overviews of the principles of different operators. (Also refer to the literature references listed in Appendix G under Edge Enhancement.)

B.2 EDGE ENHANCEMENT OPERATORS

B.2.1 ROBERTS EDGE ENHANCEMENT OPERATOR

The Roberts edge enhancement operator is a local operator, and makes use of gradient determination. The magnitude m(i,j) of the intensity gradient, and the possible direction θ(i,j) of an edge, in a digitized image - with picture elements ("pixels") as in Figure B.1 - are determined as follows:

f(i-1,j-1)	f(i,j-1)	f(i+1,j-1)
f(i-1,j)	**f(i,j)**	f(i+1,j)
f(i-1,j+1)	f(i,j+1)	f(i+1,j+1)

FIGURE B.1: <u>Digitized image with pixel f(i,j) and its eight neighbours</u>

$m(i,j) = [a^2 + b^2]^{1/2}$ (B.1)

$\theta(i,j) = \arctan(b/a) + 90°$ (B.2)

with:-

$a = f(i+n,j) - f(i,j)$ (B.3)

$b = f(i,j+n) - f(i,j)$ (B.4)

i,j: image coordinates (measured in [pixels] from the image reference point; typically in the range 0 to 511, or 1 to 512)

f(i,j): grey-scale value of the pixel with image coordinates (i,j)

In order to save computational time, the squares and the square root in (B.1) are often avoided by making use of absolute values:

$m(i,j) = |a| + |b|$ (B.1a)

(The "n" in equations (B.3) and (B.4) is a small integer - typically n=1.) Different variations of (B.3) and (B.4) are used, such as:

$a = f(i+n,j+n) - f(i,j)$ (B.5)

$b = f(i,j+n) - f(i+n,j)$ (B.6)

When (B.5) and (B.6) are used, (B.2) changes to:

$\theta(i,j) = \arctan(b/a) + 45°$ (B.2a)

Once the gradient magnitude has been determined, it is compared with a threshold value in order to determine whether the specific image point can be classified as an edge point or not. It is a problem however to determine the threshold value. Although some algorithms for automatic determination of the threshold are discussed in the literature (e.g. McKEE & AGGARWAL (1975); SID-AHMED (1987) and WONG & SAHOO (1989)), this aspect still requires a lot of research. The best results still seem to be reached by determining the threshold manually through trial and error.

B.2.2 SOBEL- AND PREWITT EDGE ENHANCEMENT OPERATORS

The Sobel- and the Prewitt edge enhancement operators (both local operators) determine the magnitude of the intensity gradient by equation (B.7), and the direction of the edge by (B.8):

$m(i,j) = [S_x^2 + S_y^2]^{1/2}$ (B.7)

$\theta(i,j) = \arctan(S_x/S_y)$ (B.8)

with:-

$S_x = [f(i+1,j-1) + C.f(i+1,j) + f(i+1,j+1)] - [f(i-1,j-1) + C.f(i-1,j) + f(i-1,j+1)]$ .....(B.9a)

$S_y = [f(i-1,j+1) + C.f(i,j+1) + f(i+1,j+1)] - [f(i-1,j-1) + C.f(i,j-1) + f(i+1,j-1)]$ .....(B.9b)

For the Sobel edge enhancement operator, C=2 in (B.9), while C=1 for the Prewitt operator - refer to NEVATIA (1982, p.102). Again absolute values - as in (B.1a) - are often used in (B.7).

These operators also require threshold values - as discussed in Section B.2.1 above.

B.2.3 THE LAPLACE EDGE ENHANCEMENT OPERATOR

The Laplace edge enhancement operator is also a local operator, and it makes use of a second order differentiation in order to determine the gradient m(i,j) of an image function f(i,j). It can however not determine the direction of an edge; and image noise is enhanced because of the double differentiation. One version of the discrete Laplacian, for determining the magnitude of the intensity gradient, is (BALLARD & BROWN (1982)):

$$L(i,j) = f(i,j) - 0{,}25[f(i,j+1) + f(i,j-1) + f(i+1,j) + f(i-1,j)] \qquad (B.10)$$

This operator also requires a threshold value - as discussed in Section B.2.1 above.

B.2.4 TEMPLATE MATCHING

This regional operator technique is based on the definition of a number of standard profiles (templates) of intensity changes, to be compared with an image in which edges have to be enhanced - refer to BALLARD & BROWN (1982, p.79). Examples of typical binary templates are shown in Figure B.2. (The templates can of course also be much larger, and with different profiles.) The template in Figure B.2a can be used for enhancement of vertical edges, while that in Figure B.2b is used for horizontal edges. (These templates are sometimes called Kirsch-profiles - BALLARD & BROWN (1982, p.79).)

```
0 0 1 1      0 0 0 0
0 0 1 1      0 0 0 0
0 0 1 1      1 1 1 1
0 0 1 1      1 1 1 1
  (a)          (b)
```

FIGURE B.2: <u>**Examples of templates for edge enhancement**</u>

This method can also be used to find a pre-defined object in an image. For such an application, a template is scanned through the image, and a correlation factor is determined for each template position. It is evident that the template must match the object which is searched in form, size, orientation, and intensity.

B.2.5 CANNY OPERATOR

The local operator of CANNY (1980) involves mathematically obtaining a convolution operator in the spatial or image domain, of which the output will satisfy the following conditions:

a. High signal-to-noise-ratio (S/N) - i.e. very few false indications of edge points.

b. Thin edges - i.e. only one pixel must be marked for each edge.

Part of this operator involves the use of spatial differentiation - such as one of the operators described in Sections B.2.1 to B.2.3 above.

(Besides the abovementioned literature reference, CHRISTIANSEN (1990) also presents an extensive discussion of the Canny operator.)

B.2.6 GEUEN AND LIEDTKE OPERATOR

The Geuen and Liedtke operator is based on the principles of human contour perception - refer to GEUEN (1982) and LIEDTKE (1982). A bandpass filter, resembling the spatial frequency response (or Modulation Transfer Function) of the human eye - refer to SHAPLEY & TOLHURST (1973) - is realized by combining the outputs of different lowpass filters. These lowpass filters are realized by calculating the mean values of pixels within different sized rectangular windows in an image. (Each filter's window is scanned through the image, line by line.)

According to GEUEN (1983), the main disadvantages of this operator are that it produces wide edge contours, as well as gaps in the edges.

B.2.7 MARR AND HILDRETH OPERATOR

The Marr and Hildreth operator is also based on properties of the human visual system, and is described by HILDRETH (1982), MARR (1982), MARR & HILDRETH (1980), and MARR & POGGIO (1979). The operator first makes use of a lowpass filter action in the spatial frequency domain, in order to blur edge structures smaller than a pre-defined threshold, and then it uses the Laplacian operator (refer to Section B.2.3 above) in order to determine edges.

B.2.8 HUECKEL OPERATOR

A simplified model of an ideal edge - as defined by HUECKEL (1971, 1973) - is shown in Figure B.3. An edge at an angle θ and distance r from the centre separates two regions of brightness b and $b + h$. The aim of Hueckel's operator is to determine the parameters *r*, ϴ, *b*, and *h* of the step function that matches best with a given image region. This is done by scanning the edge model with different parameter values, over the image.

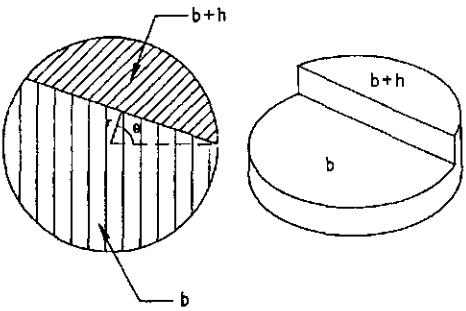


FIGURE B.3: Edge template as defined by HUECKEL (1971, 1973)

HUECKEL (1971, 1973) was successful in obtaining a partly analytical method to determine the parameters *r*, ϴ, *b*, and *h*. (The method first makes use of a low pass filter in the spatial frequency domain.) The algebraic details of this method are complex however.

B.2.9 O'GORMAN OPERATOR

Although scanning an image with the Hueckel operator produces good results, it has the disadvantage of being computationally complex - making it slow. MÉRÕ & VASSY (1975) and O'GORMAN (1978) have therefore modified the Hueckel operator in order to speed it up. CHRISTIANSEN & NEL (1989) obtained even better speed, by modification of the O'Gorman operator. (Besides the abovementioned literature references, CHRISTIANSEN (1990) also presents extensive discussions of these operators and the modifications.)

B.2.10 FILTERING IN THE FREQUENCY DOMAIN

The basic principles of this technique - as discussed by NEL (1987) - are the following:

a. A two-dimensional fast Fourier transform (FFT) is applied to the image, in order to transform it from the spatial domain to the frequency domain.

b. Since high frequencies correspond to large intensity differences in the image, a high-pass filter is applied to the frequency domain image.

c. The filtered image is then transformed back to the spatial domain, with only the edges (or areas of large intensity changes) left.

According to NEL (1987, p.20) the two major problems associated with this technique are:

a. The method is very computer intensive - even for relatively small images.

b. The technique renders different results for images appearing to be similar.

B.3 CHOICE OF A SUITABLE DATA REDUCTION AND EDGE ENHANCEMENT ALGORITHM FOR USE IN A MILKING ROBOT

B.3.1 CRITERIA FOR CHOOSING THE BEST EDGE ENHANCEMENT ALGORITHM

With the different techniques and algorithms for edge enhancement in mind, the question arises as to which one of these techniques will be the best for application as part of a milking robot. Unfortunately, the answer is not obvious, nor easily obtainable - even when using one of the various methods described in the literature to evaluate and compare different edge enhancement algorithms (e.g. ABDOU & PRATT (1979); FRAM & DEUTSCH (1975); NEL (1987); PELI & MALAH (1982); PRATT (1978); and SHAW (1979)).

Instead of spending too much time during this project on the issue of choosing the best edge enhancement algorithm, a separate investigation into this aspect was suggested by GOUWS (1988a). This gave rise to the research as reported by CHRISTIANSEN (1990) and FREESE (1990). This decision was taken for two main reasons:

a. The topic covers a vast field of research - which could easily take up all the time available for the wider research on milking robots.

b. Edge enhancement can be implemented as a software module of the milking robot's machine perception subsystem. Such a software module can easily be upgraded, should a more suitable algorithm become available.

CHRISTIANSEN (1990) suggested an evaluation technique based on a combination of subjective and non-subjective evaluation criteria:

a. Subjective evaluation. A group of people is asked to compare the edge images obtained with different edge enhancement algorithms, with the original image. The edge images are then rated on a scale from 1 (edge image a very poor representation of the original) to 5 (edge image a very good representation of the original). The process is repeated with several images. The mean and the standard deviation for each operator are then used as the subjective rating of the specific edge enhancement operator.

b. Non-subjective evaluation. Different edge enhancement algorithms are evaluated in terms of:
   i. The quality of its output - e.g. continuity and thinness of edges; ratio of edges found to edges missed; and amount of false edges indicated.
   ii. The characteristics of the algorithm - e.g. speed; and memory usage.

B.3.2 CHOOSING AN EDGE ENHANCEMENT ALGORITHM FOR A MILKING ROBOT

After performing a qualitative choice reduction, CHRISTIANSEN (1990) chose the following five edge enhancement algorithms to be evaluated by means of his evaluation technique:

a. Canny operator (Section B.2.5);
b. Geuen and Liedtke operator (Section B.2.6);
c. Marr and Hildreth operator (Section B.2.7);
d. Sobel operator (Section B.2.2); and
e. O'Gorman operator (Section B.2.9).

Each of the algorithms were applied to four different images, after which they were evaluated by means of the abovementioned subjective and non-subjective criteria. In this evaluation, the **Sobel operator** fared the best. (Figure B.4 contains edge images of a cow's udder - as obtained with the abovementioned five edge enhancement algorithms.)

FREESE (1990) compared the performance of the distributed associative memory (DAM) operator - implemented by means of neural network techniques (also refer to WECHSLER & ZIMMERMAN (1988)), with that of the Sobel operator. After thorough investigation, it was concluded that the Sobel operator did not only deliver better edge images than the DAM operator, but it was also much faster.

ELSTER & GOODRUM (1991) have also evaluated several edge enhancement algorithms, as part of an automated egg sorter. Their conclusion was: "The use of a Sobel convolution operator enhanced the image better than other methods investigated [...]."

From the results obtained in different evaluations, it is clear that the Sobel operator provides a very suitable solution to the edge enhancement problem, for the milking robot.

B.4 CONCLUSION

In this appendix, a brief overview of edge enhancement techniques was presented. Because the topic is a vast research field on its own, it was not addressed in too much detail as part of this research project. Preliminary work and suggestions by the author did however give rise to other researchers investigating edge enhancement - inter alia methods for choosing the best operator for a specific task. From the author's own experience, the **Sobel operator** was qualitatively chosen to be implemented as part of the milking robot's machine perception subsystem. This qualitative choice was confirmed by the more extensive, and scientifically based investigations of other researchers.

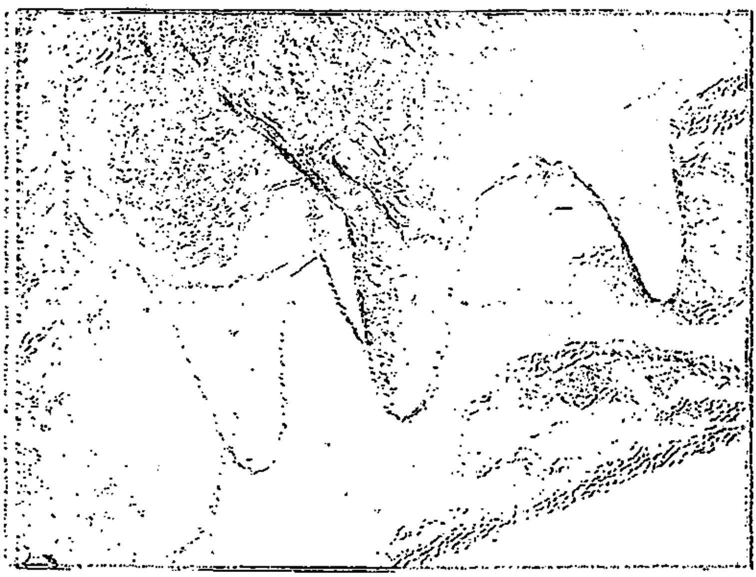


FIGURE B.4a: Edge image obtained with Canny operator

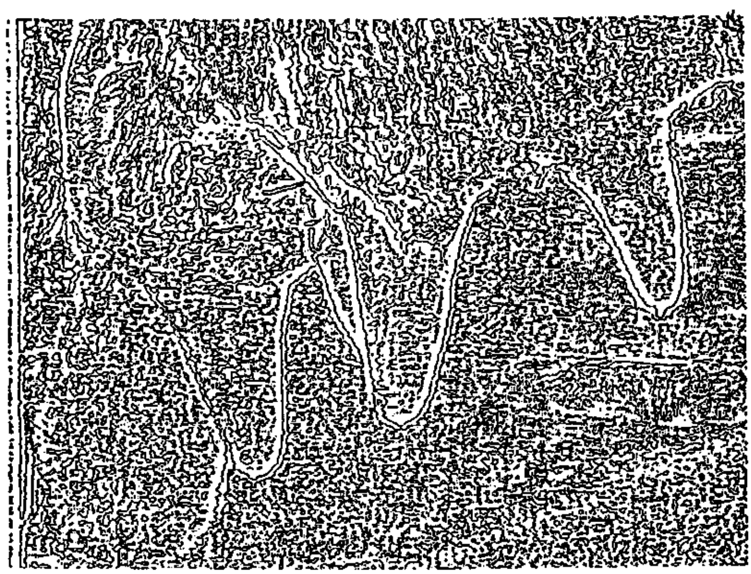


FIGURE B.4b: Edge image obtained with Geuen and Liedtke operator

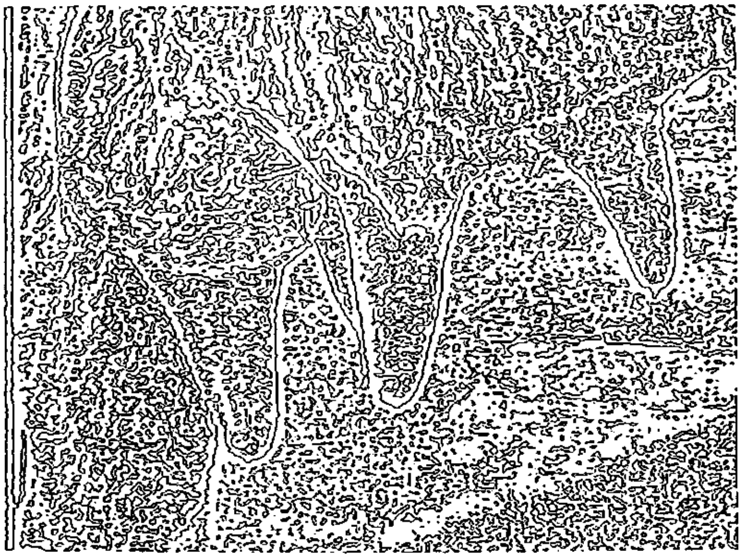


FIGURE B.4c: Edge image obtained with Marr and Hildreth operator

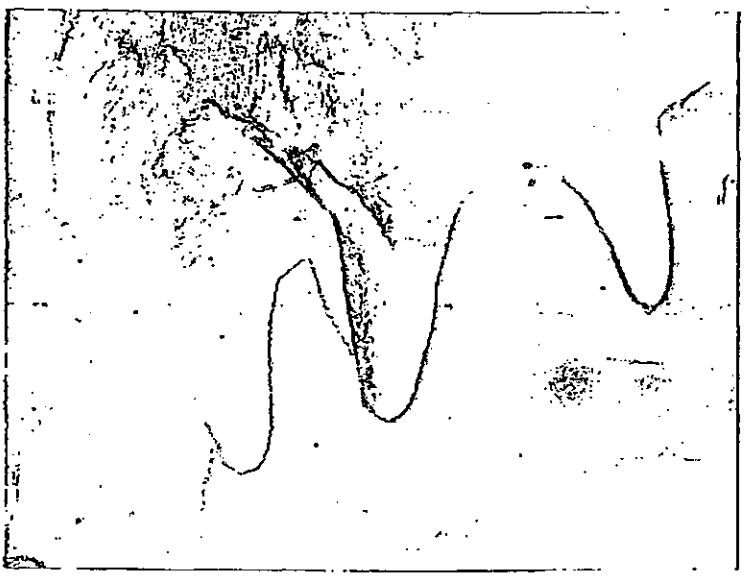


FIGURE B.4d: Edge image obtained with Sobel operator

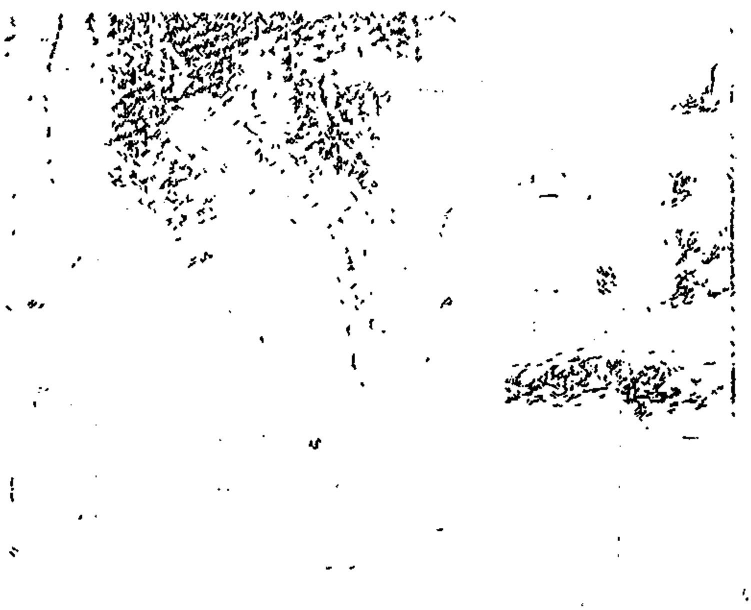


FIGURE B.4e: Edge image obtained with O'Gorman operator

*****

APPENDIX C

THE HOUGH TRANSFORM

C.1 INTRODUCTION

HOUGH (1962) suggested a technique for locating lines in a digital image (typically an edge enhanced image as described in Appendix B), by mathematically detecting collinear points. The method involves the transformation from one parameter space/plane (e.g. two-dimensional image coordinates) into another parameter space/plane (e.g. a plane described by the parameters of a straight line). (Refer to SILJAK (1968) for a general discussion of parameter space techniques and transformations.)

The original method proposed by HOUGH (1962) was used for detecting parametric curves in images (e.g. $y = mx + c$). The Hough transform differs from ordinary curve fitting in that the former is suitable for detecting multiple - even overlapping - curves in one image. The Hough transform was generalized by BALLARD (1981) for detection of edges with arbitrary shapes - i.e. non-analytic curves. The latter however makes use of template matching techniques, limiting its applicability. (Refer to the discussion of template matching in Section B.2.4.)

From a literature survey regarding the Hough transform (refer to Appendix G), it was concluded that the high level principles are mostly described, while neglecting the practical aspects of implementing the transform. Furthermore, the applications are often limited to straight lines. This appendix is included in order to provide a theoretical background for using the Hough transform for localising a cow's four teats in an image (Section 3.4.4).

C.2 DETECTION OF STRAIGHT LINES

The first example presented in this appendix illustrates the finding of a straight line in an image - as shown in Figure C.1. One form of the equation for a straight line is shown in equation (C.1):

$$R = x.\cos\theta + y.\sin\theta \qquad \text{(C.1)}$$

with:- (refer to Figure C.1)

- R: shortest distance between the line and the image plane's point of reference (measured in [pixels] in a digitized image)
- θ: angle of line R relative to one of the axes of the image coordinate system - [°] or [rad]
- x,y: image coordinates of points on the line (measured in [pixels] in a digitized image, relative to the image plane's point of reference)

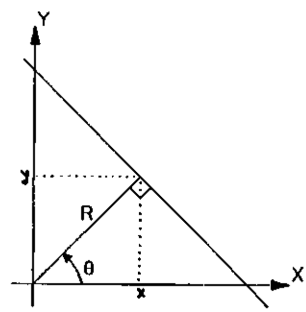


FIGURE C.1: Line as represented by eq.(C.1)

In equation (C.1) there are four variables, namely x, y, R, and θ. By varying θ between 0° and 360°, each image point (x,y) in an edge enhanced image, can be transformed into a curve in the R-θ plane. If N curves in the R-θ plane intersect, that is an indication that there are N collinear points in the image. The R-θ values at the intersection represent the distance R of the line from the image plane's origin, and its angle θ - as defined in Figure C.1.

If there are distinctive lines in an image (i.e. definite collinear points), the Hough transform will detect such collinear points, irrespective of the distances between the individual points on the line. This feature makes the Hough transform insensitive for gaps in edge enhanced lines in images; or for image noise in digitized pictures.

Equation (C.1) is preferred, instead of $y = mx + c$, for detection of straight lines by means of the Hough transform. For determining $m = (y-c)/x$, parameter c has to be stepped through a large range of values (theoretically between $-\infty$ and $+\infty$); while θ of (C.1) is limited.

As an example, consider the pixel map of a binary image with two distinctive lines in it, shown in Figure C.2.

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1
2	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0
3	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0
4	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0
5	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0
6	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0
7	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0
8	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
19	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
20	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0

FIGURE C.2: Pixel map of a simple 20x20 binary image

The top left corner of this image is chosen as the reference point; and θ is measured anti-clockwise, relative to the vertical axis (pointing downwards), and towards the shortest lines between the origin and the lines in the image (as defined in Figure C.1). R_1 and R_2 are defined and calculated as follows:

a. The shortest line between the reference point and the vertical line, intersects the vertical line at image coordinates (8;0). Therefore $R_1 = 8$.

b. The shortest line between the reference point and the inclined line, intersects the line between the two pixels with image coordinates (11;10) and (10;11). A *pseudo pixel* with coordinates (10,5;10,5) is defined at the intersection, from which R_2 is calculated as $R_2 = (10{,}5^2 + 10{,}5^2)^{1/2} = 14{,}85$.

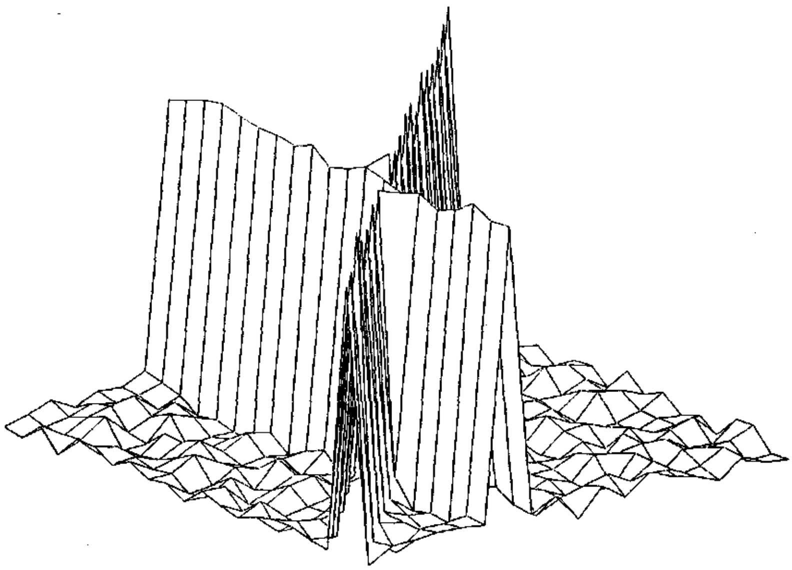
In terms of the definitions given above, and in Figure C.1, the parameters of the two lines in Figure C.2 are:

$$(R_1;\theta_1) = (8;90°) \qquad \text{(C.2a)}$$
$$(R_2;\theta_2) = (14{,}85;45°) \qquad \text{(C.2b)}$$

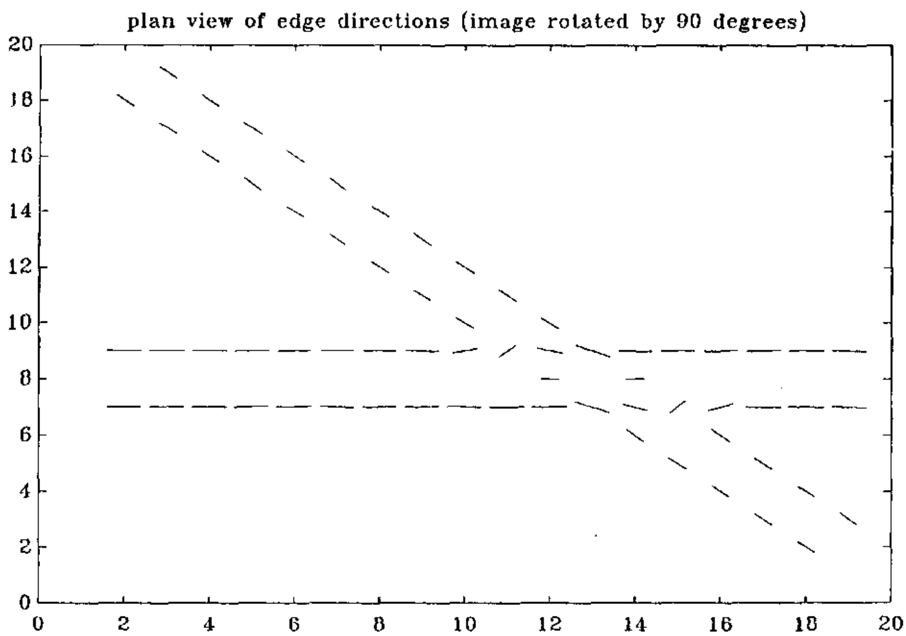
In order to perform line detection by means of the Hough transform, the following algorithm is typically used:

```
for x = 1 to x_max
 for y = 1 to y_max
  if f(x,y) > 0 then
   for θ = 0 to 180 step δθ
    R = x*cos(θ) + y*sin(θ)
    R1 = round(R)
    A(R1,θ) = A(R1,θ) + 1
   next θ
  end if
 next y
next x
```

The statement *"if f(x,y) > 0 then"* ensures that the algorithm only operates on pixels which have grey-scale values other than zero (i.e. the edge enhanced pixels in an image). A(R1,θ) is an accumulator array, keeping record of the number of occurrences of a specific value of R1 (which is R, rounded to the nearest integer) for each value of θ. To implement such an accumulator array is not without a few minor problems however. R is calculated from (C.1), which does not necessarily result in positive integer values (as is normally required for an accumulator index). Positive real values of R are therefore rounded to the nearest integer; while negative values of R are discarded, since they represent possible lines not falling in the given image plane.



(a) Mesh diagram of a simulated 20x20 pixel image



(b) Plan view of the edge directions

FIGURE C.3: Images for illustration of the linear Hough transform

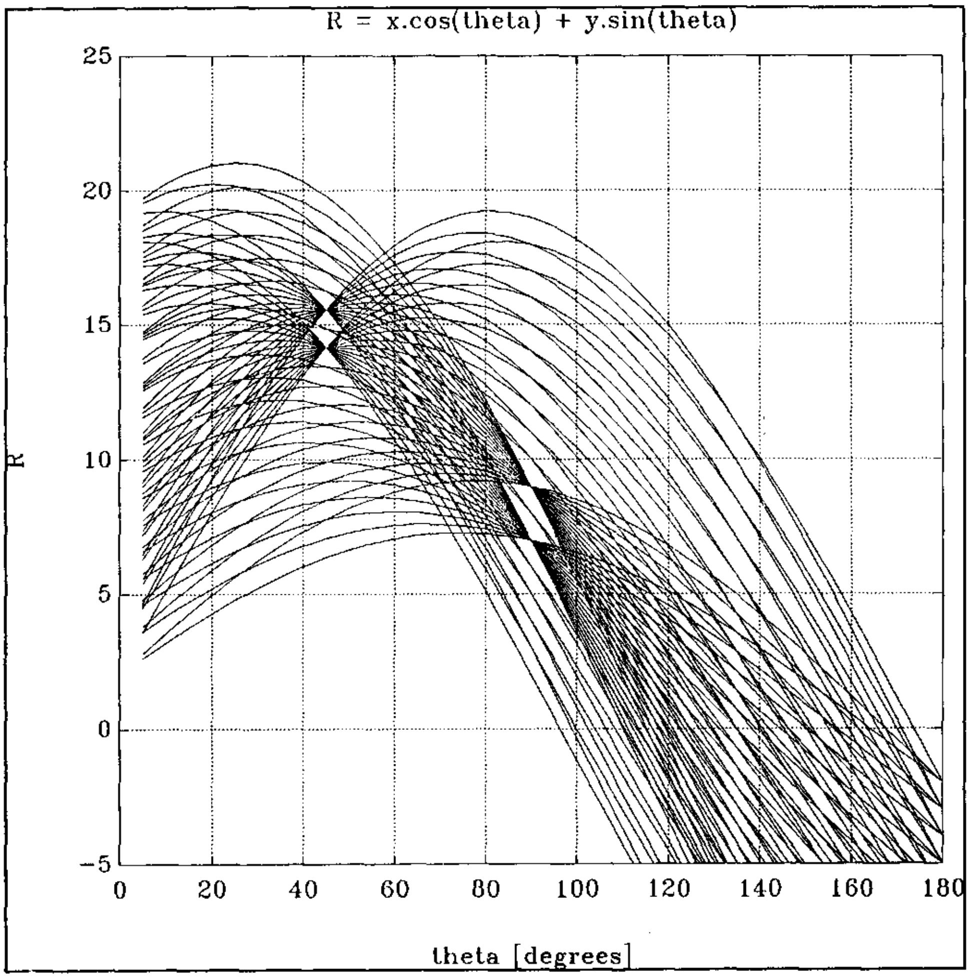


FIGURE C.4: Hough transform curves of the edge enhanced image as in Figure C.3

Each bin in the accumulator array must be capable of holding all the values assigned to it. For locating straight lines in an image of 512 x 512 pixels (typical video image), with the origin at *one of the image's corners,* $R_{max} \approx 724$. *The* resulting size of the accumulator array is 724 x (180/$\delta\theta$). Such a large accumulator array can cause computer memory problems. In this research, a *trick* that was found to work well (depending on the nature of the image analyzed) is to consider only each n-th pixel in the image (typically every second or third one), thereby scaling down the required accumulator size by 1/n. This trick works since the Hough transform is not sensitive for gaps in the lines to be detected.

Appendix E contains the summary of a simple PC-MATLAB program SOBHOU.M which was used to illustrate the above principles by making use of the binary image in Figure C.2, with *added image noise.* The program is used to execute the following steps:

a. A simulated 20x20 pixel image is generated by adding a matrix of random numbers (between 0 and 0,1) to a matrix of numbers as shown in Figure C.2. A mesh diagram of the "noisy" image is shown in Figure C.3a.

b. The program then makes use of the Sobel operator to enhance edges in the image (refer to Appendix B). A simple plan view of the edge directions is shown in Figure C.3b.

(Note that two lines are shown for each edge. This is because the Sobel operator detects both the transition from the background to the line, and the transition from the line to the background.)

c. Next the Hough transform, as described in the simple algorithm above, is applied to the edge enhanced image - resulting in the set of curves shown in Figure C.4.

From the curves in Figure C.4 it is derived that the edge enhanced image contains four sets of collinear points - characterised by the (R;θ) values of the four distinctive node points in the figure. By inspection, the following (R;θ) values are derived from the node points in Figure C.4:

$$(R_a;\theta_a) = (14{,}15\ ;\ 45°) \quad (C.3a)$$
$$(R_b;\theta_b) = (15{,}55\ ;\ 45°) \quad (C.3b)$$
$$(R_c;\theta_c) = (7\ ;\ 90°) \quad (C.3c)$$
$$(R_d;\theta_d) = (9\ ;\ 90°) \quad (C.3d)$$

The values in equation (C.3) describe the edge lines as represented in Figure C.3b. When the average values of $(R_a;\theta_a)$ and $(R_b;\theta_b)$, and $(R_c;\theta_c)$ and $(R_d;\theta_d)$ are calculated, they correspond to the parameters in equation (C.2).

When the maxima in the accumulator array (as used in the program SOBHOU.M) are determined, the exact values as in equation (C.3) are not obtained, for the following reasons:

a. The accumulator array makes use of rounded values of R as one of its indexes. Therefore only integer values of R can be derived from the accumulator array.

b. Due to the rounding of R values, false node points can be indicated.

The (R;θ) values derived from the accumulator array are:

$$(R_e;\theta_e) = (14\ ;\ 45°) \quad (C.4a)$$

$$(R_f;\theta_f) = (16\ ;\ 45°) \quad (C.4b)$$

$$(R_g;\theta_g) = (7\ ;\ 90°) \quad (C.4c)$$

$$(R_h;\theta_h) = (9\ ;\ 90°) \quad (C.4d)$$

The abovementioned problem is less serious in larger images, where the typical ratio of rounding error to line distances will be smaller.

C.3 DETECTION OF CIRCLES

The detection of circles by means of the Hough transform is slightly more complex than detecting straight lines. This is because in general a circle has three parameters; and thus requires a three-dimensional accumulator array. The general equation for a circle is:

$$(x - x_r)^2 + (y - y_r)^2 = r^2 \quad (C.5)$$

with:-

- r: radius of the circle (measured in [pixels] in a digitized image)
- x_r, y_r: translation of the circle's centre, relative to the image plane's reference point [pixels]
- x,y: image coordinates of points on the circle [pixels]

A three-dimensional array is required in the form $A(r,x_r,y_r)$ in order to perform circle detection by means of the Hough transform. Although it is possible to form such an array, not all computer languages support such a structure - with PC-MATLAB being one that does not support it. In order to overcome this problem, an array of two-dimensional accumulators can be used. However, such a system requires good management of the data in the arrays.

Appendix E contains the summary of a PC-MATLAB program HOUCIR.M written to illustrate the detection of circles. The program executes the following steps:

a. A simulated 20x20 pixel image is generated, based on values of $(r;x_r;y_r)$, specified by the user. The example in the program uses the values:

$$(r\ ;\ x_r\ ;\ y_r) = (7\ ;\ 8\ ;\ 10) \quad (C.6)$$

b. Next the Hough transform is applied to the image. Ranges of relevant values are chosen for y_r and x_r. For each value of y_r, the values of x_r, x, and y, are stepped through their full ranges; and r is calculated from (C.7):

$$r = ((x - x_r)^2 + (y - y_r)^2)^{1/2} \quad (C.7)$$

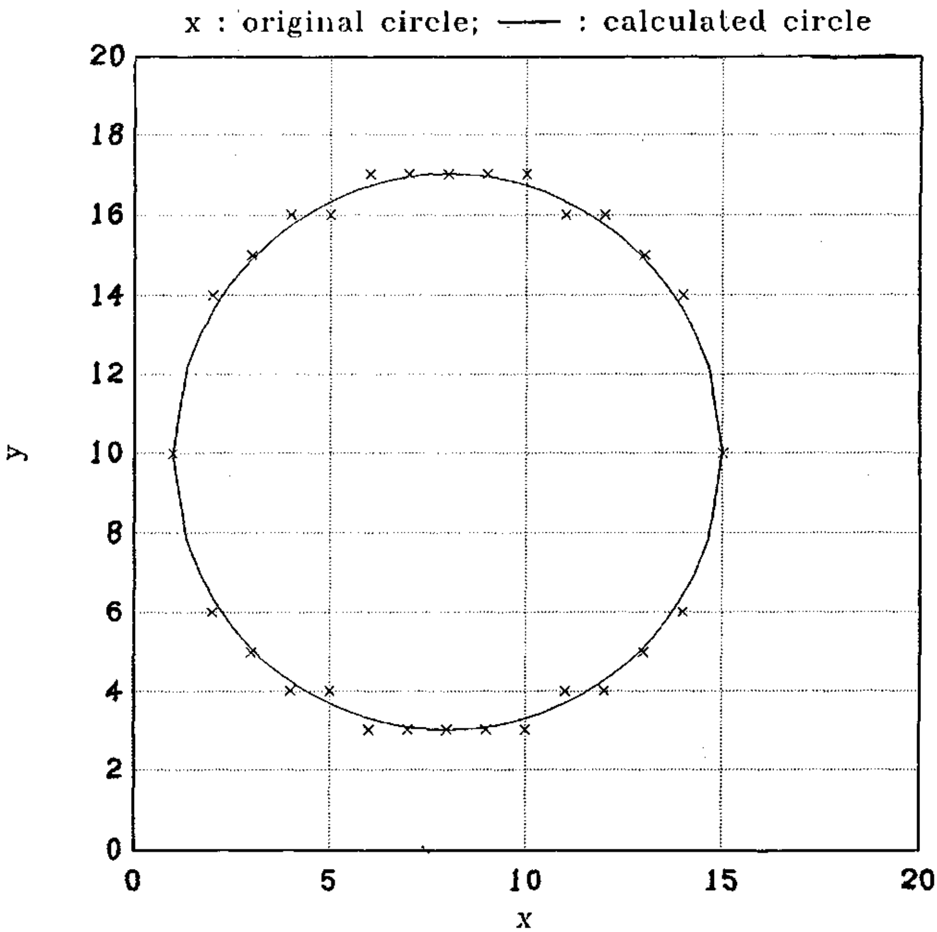


FIGURE C.5: Circle (solid line) derived form the Hough transform applied to the pixel image (x)

c. For a specific value of y_r, the values of an accumulator array $A(r,x_r)$ are incremented. Once all x_r, x, and y have been used, the maximum value of the $A(r,x_r)$ accumulator is determined. The indexes of A at the maximum, and the specific value of y_r, represent possible circles in the image, of radius r, and displaced from the origin by x_r and y_r. These values are stored for later use.

d. The latter step is repeated for all chosen values of y_r. (The same accumulator array is initialised and is re-used for every y_r.)

e. The last step is to determine the maximum of all the maxima (as determined in steps (c) and (d)); and the x_r, y_r, and r corresponding to this maximum. These three parameters are the most likely parameters of a circle in the image. By means of the program HOUCIR.M - which implements the above steps - the exact parameters as in (C.6) were derived. Figure C.5 shows the simulated edge pixels (denoted by x), representing the input image; while the solid line circle was drawn from the parameters derived from the accumulator arrays. (From this example, it is confirmed that the Hough transform is not sensitive for gaps in the pixel image; *nor is it influenced by the discrete nature of* the image.)

C.4 DETECTION OF PARABOLAS

The detection of parabolas by means of the

Hough transform is even more complex than detecting circles, due to one more parameter being added. A four-dimensional accumulator array is therefore required - which is not a simple matter. (In the Turbo Pascal 5.5 Handbook, SWAN (1989, p.106) says: "Be careful when declaring multidimensional arrays not to get carried away. While you can have up to 255 multiple dimensions in Turbo Pascal, there are few cases where more than three do much good." Furthermore, even if a multi-dimensional array might be used, there is a limit on its overall size - due to computer memory limitations.)

Consider a parabola (in an axes system termed x_1 and y_1) as represented by equation (C.8):

$$y_1 = a.x_1^2 \qquad (C.8)$$

If the x_1y_1-axes are now rotated by an angle θ, and displaced by (x_r;y_r), relative to a fixed set of xy-axes, then the (x;y) coordinates of this rotated and displaced parabola is given by (C.9) - GOLDSTEIN (1978, p.99).

$$x = x_1.\cos\theta + y_1.\sin\theta + x_r \qquad (C.9a)$$
$$y = -x_1.\sin\theta + y_1.\cos\theta + y_r \qquad (C.9b)$$

with:-

- x,y: image coordinates of points on the parabola (measured in [pixels] w.r.t. the fixed xy-axes)
- x_1,y_1: image coordinates of points on the parabola (measured in [pixels] w.r.t. the moving x_1y_1-axes)
- x_r,y_r: translation of the x_1y_1-axes relative to the fixed xy-axes
- θ: angle of rotation of the x_1y_1-axes relative to the fixed xy-axes - [°]

In order to localise and describe a parabola such as represented by (C.8) and (C.9), four parameters are required, with a resulting accumulator array A(a;θ;x_r;y_r). Again, the problem of a multi-dimensional accumulator array can be overcome by making use of multiple two-dimensional accumulators. For detecting parabolas, such a system requires even better management of the data in the accumulators, than for detecting circles, however.

Appendix E contains the summary of a PC-MATLAB program HOUPAR.M written to illustrate the detection of parabolas. The program executes the following steps:

a. A simulated pixel image of a twisted and displaced parabola is generated, based on values of (a;θ;x_r;y_r), specified by the user. (The image is "contaminated" with a straight line, in order to show that the Hough transform is not hampered by other curves in the image.) The example in the program uses the following parameter values for the parabola:

$$(a;\theta;x_r;y_r) = (0{,}2;\ 10°;\ 11;\ 17) \qquad (C.10)$$

b. Next the Hough transform is applied to the image. Ranges of relevant values are chosen for θ, a, and x_r. These three values are used as parameters in three layers of *for (...) = $(...)_{min}$ to $(...)_{max}$* loops. Within these three loops, y_r is calculated for each θ, a, x_r, x, and y, by making use of (C.11). (Because of the rotation of the parabola, two values of y_r can result at each calculation point - therefore the two equations in (C.11).)

c. For a specific value of θ, and a specific value of a, the values of an accumulator array A(y_r,x_r) are incremented. Once all x_r, x, and y have been used, the maximum value of the accumulator is determined. The indexes of A at the maximum, represent possible y_r and x_r values; and are stored with the specific values of θ and a, for later use.

d. The latter step is repeated for all chosen values of a; and the whole process is then repeated for all chosen values of θ. (The same accumulator array is initialised and is used every time.)

e. The last step is to determine the maximum of all the maxima (as determined in (c) and (d)); from which the most likely parameters of a parabola in the image are derived.

With the program HOUPAR.M, the exact parameters as in (C.10) were derived by means of the above steps; while the presence of the straight line in the image had no influence at all. Figure C.6 shows the simulated edge pixels (denoted by x for the parabola, and by o for the straight line), representing the input image; while the solid line parabola was drawn from the parameters derived from the accumulator arrays. (Again it can be seen from the example that the Hough transform is not sensitive for gaps in the pixel image; nor for the discrete nature of the image.)

$$y_{r1} = y + \frac{-\cos\theta + \sqrt{\cos^2\theta - 4(x_r - x)(a.\sin\theta)}}{2a} - \left(\frac{-\cos\theta + \sqrt{\cos^2\theta - 4(x_r - x)(a.\sin\theta)}}{2.a.\sin\theta}\right)^2 a.\cos\theta$$

.....(C.11a)

$$y_{r2} = y + \frac{-\cos\theta - \sqrt{\cos^2\theta - 4(x_r - x)(a.\sin\theta)}}{2a} - \left(\frac{-\cos\theta - \sqrt{\cos^2\theta - 4(x_r - x)(a.\sin\theta)}}{2.a.\sin\theta}\right)^2 a.\cos\theta$$

.....(C.11b)

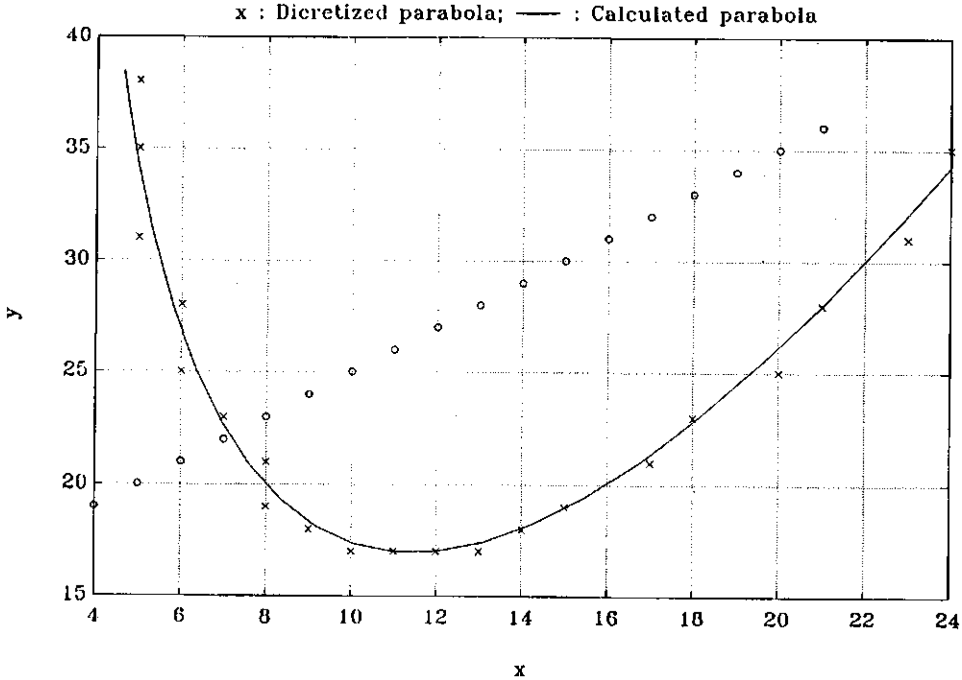


FIGURE C.6: Parabola (solid line) derived from the Hough transform applied to a pixel image containing both a parabola and a straight line

C.5 CONCLUSIONS

The localisation of different types of parametric curves by applying the *Hough transform* to edge enhanced images, was illustrated in this appendix by means of examples. The insensitivity of the Hough transform for gaps in the edges, and for discretisation noise was also illustrated.

Detection of curves such as circles and parabolas require multi-dimensional accumulator arrays. This is a problem in some computer languages, and it also requires extensive computer memory. Although it was illustrated that some of these practical difficulties can be overcome by means of well planned data management - e.g. by using multiple two-dimensional accumulator arrays - there are still problem areas which require further research.

The detection of parabolas - rotated and displaced from the origin of the reference axes - is of special importance in the milking robot context, since the edge enhanced images of a cow's teats resemble parabolas. This aspect is addressed in more detail in Chapter 3 - making use of the information presented in this appendix.

APPENDIX D

DICTIONARY OF TERMS

In this appendix, a number of terms which are used in the dissertation, are briefly explained. The dictionary of terms is included since the dissertation covers a number of topics which are not commonly related - such as agricultural automation; dairy automation; machine perception; robotics; and control systems theory and application. The dictionary is by no means complete, but is merely an attempt to explain some of the most important terms.

Some of the explanations are purely the author's own definitions, which might differ slightly from that found in a dictionary or in the literature. This is done in order to adapt to the specific context in which the terms are used in the dissertation. (Underlined words in the explanations are included somewhere else in the dictionary.)

TERM	EXPLANATION
Action volume	Volume in which a milking robot must be able to operate.
Actuators	Converters from various types of energy to mechanical energy (e.g. electrical motors, or hydraulic cylinders).
Agronomy	Cultivation of soil by farmers.
Agro-socio-economic	Social and economic factors related to the agricultural sector of a specific community.
Animal husbandry	The housing, feeding, breeding, and utilisation of farm animals.
ASAE	American Society of Agricultural Engineers; 2950 Niles Road, St.Joseph, Michigan, U.S.A.
Automation	The enhancement or replacement of muscle-, sensing-, and mental power, by means of a machine. In the case of an automated process, very little or no inputs and supervision are required from an operator (depending on the level of automation). Sensors are used to observe the machine's actions, while a computer is used to generate commands, and to make control decisions. SULTAN & PRASOW (1964) define automation as *"[...] the use of machines to run machines"*. The term mechanisation is often wrongly used as a synonym for automation.
Bit	Acronym for "binary digit". A bit is either a "0" or a "1"; and is used in computers for the representation of numbers. (Refer to pixels below.)
Control system	A device which regulates the flow of energy, matter, or other resources - by making use of feedback principles. It develops a manipulated variable, based on a command signal. (Refer to ANSI (1963, 1966) for a complete list of terminology for control systems.)
Edgel	Acronym for "edge pixel". Edgels are the pixels in an edge enhanced image (refer to Appendix B).

TERM	EXPLANATION
Feedback control	The principle of comparing a system's actual output with the desired output, and of controlling the system's output, based on the difference between these two quantities. (The principle was first formulated by BLACK (1934).)
IEEE	Institute of Electrical and Electronics Engineers, Inc.; 345 East 47 Street, New York, U.S.A.
IMAG	Instituut voor Mechanisatie, Arbeid en Gebouwen; Mansholtlaan 10-12, Wageningen, The Netherlands
Image processor	Special form of a signal processor, used for processing and conditioning of computerized images.
Individual quarter milking machine	A milking machine for which the vacuum levels of the four teatcups can be individually controlled. With such a machine, the four quarters of a cow's udder can be milked individually, and the rate of milking can be adapted to the characteristics of the individual teats.
Lactation	The period during which a cow produces milk (normally in the order of 300 days, after which she must first give birth to a calf again).
Limit cycle	Sustained oscillation in a servomechanism - even in the absence of an input to the system. This phenomenon is caused by non-linearities (such as gear backlash, electronic saturation, etc.) in control systems. (Refer to SHINNERS (1979, p.397), or to GOUWS (1985) for examples.)
Machine perception	Perception by a computer, based on signals from one or more sensors. A machine perception system typically consists of one or more types of sensors (such as television cameras, ultrasonic sensors, infrared sensors, radar, tactile sensors, etc.), and a signal processor.
Machine vision	Perception by a computer, based on visual sensory inputs - GEVARTER (1984, p.87). A machine vision system typically consists of one or more television cameras, and an image processor. (Machine vision is thus a subset of machine perception.)
Mechanical manipulator	Electronically or computer-controlled mechanical arm and/or hand, used for manipulation of objects.
Mechanisation	The enhancement or replacement of muscle power by means of a machine. A mechanised process requires an operator to generate commands, to observe the machine's actions, and to make decisions in order to control the machine's execution of a task. The term automation is often wrongly used as a synonym for mechanisation.
Milking machine	Machine used to extract milk from the udder of a cow. (For a complete list of terminology for milking machines, refer to ASAE (1987b, pp.119-121).)
Milking machine cluster	Group of four teatcups.
Milking robot	Machine used for automatically (i.e. without human aid) attaching the teatcups of a milking machine to the teats of a cow.

TERM	EXPLANATION
Monte-Carlo simulation	In contrast to the analytical solution of a problem with many variables (e.g. determination of the sensitivity of a camera model to small changes/errors in the data used to derive the model), the Monte-Carlo method is a stochastic simulation of the problem, in which random values (within pre-defined bounds) are assigned to the variables. The simulation is repeated a large number of times, and conclusions are then drawn from the average and the standard deviation values.
Pattern recognition	The term is used in the context of machine perception, where it refers to one of the steps involved in interpreting scenes and images.
Pixel	Acronym for "picture element". In order that an image can be displayed on a video monitor, the image must be digitized. Such an image typically consists of an array of 512 x 512 pixels, each represented by an 8 bit number (i.e. discretized in 2^8 = 256 grey levels).
Robot	The technology of electronically or computer-controlled mechanical manipulator systems or automatons which are able to perform activities and intellectual functions originally performed by man - NEUHEUSER (1989).
SAE	Society of Automotive Engineers, Inc.; 400 Commonwealth Drive, Warrendale, PA 15096-0001, U.S.A.
Servomechanism	A combination of the words "servant" and "mechanism", which refers to any system in which feedback is used in order to realize a control system. (Refer to HAZEN (1934).)
Signal processor	Circuits and algorithms implemented for conditioning and processing of signals derived from sensors. (A digital signal processor is implemented by means of computer hardware and software, while an analog signal processor makes use of analog electronic filters.)
Teatcup	Rubber lining within a metal shell, fitting over a cow's teat, in order to extract milk from the teat. (Refer to CASTLE & WATKINS (1979, pp.163-165), for a complete description of the milking process.)
Udder	Milk-gland of a cow, with four teats (designated left front, right rear, etc.).

APPENDIX E

SUMMARIES OF COMPUTER PROGRAMS

E.1 PC-MATLAB PROGRAMS

E.1.1 CAL2D.M - DETERMINATION OF A TWO-DIMENSIONAL CAMERA MODEL, AND VERIFICATION OF THE MODEL

a. Purpose/Description:
- Determination of a two dimensional camera model (camera calibration) for points in a plane.
- Verification of the camera model.

b. Inputs:
- Two-dimensional world coordinates (x,y) of four calibration points in a plane - measured in [mm], relative to a world reference point.
- Image coordinates (U,V) of the four calibration points - measured in [pixels], relative to an image reference point.
- Two-dimensional world coordinates of five verification points (x_k,y_k) [mm].
- Image coordinates (U_k,V_k) [pixels] of the five verification points.

c. Outputs:
- Two-dimensional camera model - $x = m_1.U + c_1$; and $y = m_2.V + c_2$.
- Graphs of measured x versus measured U; calculated x versus measured U; measured y versus measured V; and calculated y versus measured V.
- Values of x and y - calculated from the camera model and the measured image coordinates of the verification points (U_k,V_k).
- Comparison of the latter with the measured verification values (x_k,y_k).
- Calculation of absolute error between calculated (x,y) and verification values (x_k,y_k).

E.1.2 CAL6.M - CALIBRATION OF TWO CAMERAS IN A STEREO VISION SET-UP

a. Purpose/Description:
- The program uses six sets of three-dimensional world coordinates (x,y,z); and two-dimensional image coordinates derived by means of two cameras in a stereo vision set-up - (U_l,V_l) and (U_r,V_r) respectively - to determine the camera models as described in Section 3.4.3.2.2.2 of the dissertation.
- Six further sets of such points are used as "verification points", to verify the derived models.

b. Inputs:
- Three-dimensional world coordinates of twelve points (x,y,z) - measured in [mm] relative to a world reference point.
- Two sets of two-dimensional image coordinates (left- and right camera) for each of the twelve points - measured in [pixels].

c. Outputs:
Mathematical models of the two cameras. (Twelve camera parameters are derived for each camera, representing the elements of matrix **C** in $(x,y,z,1)\mathbf{C} = (Ut,Vt,t)^T$ - *refer to* equations (3.6), (3.18) and (3.19) in the dissertation.)

E.1.3 THREE-D.M - LOCALISATION OF A THREE-DIMENSIONAL POINT, FROM ITS STEREO IMAGE COORDINATES, AND FROM THE CAMERA MODELS DERIVED BY MEANS OF CAL6.M

a. Purpose/Description:
- This PC-MATLAB program makes use of stereo vision techniques and the camera model described by BALLARD & BROWN (1982, p.485) to determine the three-dimensional world coordinates of a point, from two sets of image coordinates.
- Verification of the calculated three-dimensional world coordinates.

b. Inputs:
- Camera models derived by means of CAL6.M.
- Stereo image coordinates of a point.
- Choice of camera model verification methods.
- Choice of route to follow for calculation of (x,y,z) from the two camera models, and the stereo image coordinates. (Refer to Section 3.4.3.2.2.3 of the dissertation.)

c. Outputs:
- Three dimensional world coordinates corresponding to the stereo image coordinates of a point. (These world coordinates are calculated in the same frame of reference as the world coordinates used for camera calibration in CAL6.M.)
- Results of the different verification methods.
- Results of the different calculation routes for (x,y,z).

E.1.4 MONTE.M - SENSITIVITY ANALYSIS OF THREE-DIMENSIONAL SCENE DESCRIPTION

a. Purpose/Description:
The program makes use of a Monte-Carlo type of simulation in order to determine the sensitivity of the scene description process, for random errors in the measured stereo image coordinates; and for random errors in the calibrated camera parameters.

b. Inputs:
- Camera models derived by means of CAL6.M.
- Stereo image coordinates of one or more points.

c. Outputs:
- Errors in the calculated world coordinates, due to random errors (within user-defined bounds) introduced into the image formation process (i.e. the stereo image coordinates are corrupted by noise).
- Errors in the calculated world coordinates, due to random errors (within user-defined bounds) introduced into the two cameras' parameters (i.e. the camera calibration process is corrupted by noise).

E.1.5 SOBHOU.M - ILLUSTRATION OF THE SOBEL EDGE ENHANCEMENT OPERATOR AND THE HOUGH TRANSFORM

a. Purpose/Description:
- The first part of the program generates a simulated image with two crossing lines in it, and then uses the Sobel operator for enhancement of edges in the image.
- The second part uses the Hough transform to determine the gradients and positions of the lines in the edge enhanced image.
- (Refer to Section C.2.)

b. Inputs:
Parameters of two straight lines in a simulated image of 20x20 pixels.

c. Outputs:
- Edge enhanced image.
- Parameters (distance from image origin, and gradients) of the two lines.

E.1.6 HOUCIR.M - LOCALISING A CIRCLE IN AN IMAGE BY MEANS OF THE HOUGH TRANSFORM

a. Purpose/Description:
- The first part of the program generates a simulated image with a circle in it.
- The second part uses the Hough transform to determine the radius and the position of the circle.
- (Refer to Section C.3.)

b. Inputs:
Parameters of a circle, for generation of a simulated image of 20x20 pixels.

c. Outputs:
Calculated radius, x-offset, and y-offset of the circle - relative to the image reference point.

E.1.7 HOUPAR.M - LOCALISING A PARABOLA IN AN IMAGE BY MEANS OF THE HOUGH TRANSFORM

a. Purpose/Description:
- The first part of the program generates a simulated image with a rotated parabola in it.
- The second part uses the Hough transform to determine the parameters of the parabola in the simulated image.
- (Refer to Section C.4.)

b. Inputs:
Parameters of a parabola, for generation of a simulated image.

c. Outputs:
Calculated width factor, x-offset, y-offset, and rotation angle of the parabola - relative to the image reference point.

E.1.8 HOUART.M - LOCALISING AN ARTIFICIAL COW'S TEATS BY MEANS OF THE HOUGH TRANSFORM AND MANUALLY DETERMINED EDGE COORDINATES

a. Purpose/Description:
- The first part of the program shows simple edge images of four teats on an artificial udder. The edge pixels were determined manually by means of a cursor on an edge enhanced image of the udder (Program IMPROC.PAS); and then read into this program.
- The second part uses the Hough transform to fit parabolas to the image;

and to determine the image coordinates of the teat endpoints.

b. Inputs:
Image coordinates of the edge pixels of an artificial cow's teats. (Between six and twelve pairs of image coordinates were determined for each teat - refer to Table 3.12 in the dissertation.)

c. Outputs:
- Calculated parameters of parabolas matching the teat images.
- Calculated image coordinates of the teat endpoints.

E.1.9 PLOTART.M - PLOTTING AN ARTIFICIAL COW'S TEATS AND THE CORRESPONDING HOUGH PARABOLAS

a. Purpose/Description:
- This PC-MATLAB program is used to plot the image coordinates (derived with a cursor on the image) of an artificial cow's teats; and superimposed on it the parabolas derived by means of the Hough transform (from program HOUART.M).
- (Because HOUART.M takes long to generate data, PLOTART.M is used to plot the data generated and stored by means of HOUART.M.)

b. Inputs:
- Image coordinates of edge pixels on the artificial cow's teats.
- Parameters of the parabolas matched to the teats (calculated by means of HOUART.M).

c. Output:
Plot showing the calculated parabolas superimposed on the image of the four teats.

E.1.10 HOUART1.M - LOCALISING AN ARTIFICIAL COW'S TEATS BY MEANS OF THE HOUGH TRANSFORM AND SOBEL OPERATOR DETERMINED EDGE COORDINATES

a. Purpose/Description:
- The first part of the program shows edge images of four teats on an artificial udder. The edge pixels were determined by means of the Sobel edge enhancement operator (Turbo Pascal Program IMPROC.PAS); and then read into this program.
- The second part uses the Hough transform to determine the image coordinates of the teat endpoints.

b. Inputs:
Image coordinates of the edge pixels on the artificial cow's teats. (These coordinates were determined by means of the Sobel edge enhancement operator in Program IMPROC.PAS.)

c. Outputs:
- Calculated parameters of the parabolas fitted (by means of the Hough transform) to the edge enhanced teats.
- Calculated coordinates of the teat endpoints.

E.1.11 PLOTART1.M - PLOTTING AN ARTIFICIAL COW'S TEATS (FROM SOBEL OPERATOR) AND THE CORRESPONDING HOUGH PARABOLAS

a. Purpose/Description:
- This PC-MATLAB program is used to plot the edge enhanced images (determined by means of the Sobel operator) of an artificial cow's udder; and superimposed on it the parabolas derived by means of the Hough transform (from program HOUART1.M).
- (Because HOUART1.M takes long to generate data, PLOTART1.M is used to plot the data generated and stored by means of HOUART1.M.)

b. Inputs:
- Image coordinates of edge pixels on the artificial cow's teats.
- Parameters of the parabolas corresponding to the teats (calculated by means of HOUART1.M).

c. Output:
Plots showing the calculated parabolas superimposed on the images of the four teats.

E.1.12 STECOR.M - STEREO CORRELATION

a. Purpose/Description:
- This program correlates points in stereo images, by making use of two-dimensional camera models. (The points do not have to appear in the same order in the two images.)
- The two-dimensional camera models are

used to calculate values of y and z for values of x chosen within its typical range. These (x,y,z) values are somewhere on the line passing through the image point (on the camera's imaging plane), the camera's focus point, and the world point. Only for the true x value of the world point, the models will render the (y,z) values of the world point. For any other value of x, the models will render the (y,z) values at the point where the line between the image point and the world point intersects the y-z plane at that specific value of x.
- The correlation is done by means of matching the y and z coordinates calculated from the two sets of image coordinates and the two camera models.

b. Inputs:
- Two sets of image coordinates - (U_l,V_l) and (U_r,V_r).
- Range of typical values for x.

c. Outputs:
- Calculated y and z coordinates for each of the chosen values of x.
- Table with correlation of y and z coordinates calculated from left camera's image, with y and z coordinates calculated from right camera's image.
- Table with correlation of image points in left image, with image points in right image.

E.1.13 ARMDES.M - STATIC DESIGN AND ANALYSIS OF THE ROBOT ARM

a. Purpose/Description:
- Mechanical design of a cartesian arm for the milking robot.
- The program makes use of strength of materials principles for the mechanical design and analysis of a cartesian arm for the milking robot. (A number of approximations are used, decreasing the accuracy of the results. The aim of this program is however only to provide approximate figures - within ±10% accuracy - of the static behaviour of the robot arm, under worst case conditions.)

b. Inputs:
- Choice of material to be used for the arm segments (aluminium or steel).
- Length of each arm segment.
- Allowable deflection of the hand's mounting point.
- Position and width of slots in the arm segments.
- Preferred outer dimension of the arm segments.
- Estimated maximum concentrated load at hand's mounting point.

c. Outputs:
- Inner dimension of the hollow square beams.
- Actual deflections (due to various bending and torsional moments) of each of the arm segments.
- Errors in the robot hand's x-, y-, and z-positions due to the deflections.

E.1.14 ACTDES.M - DESIGN OF THE ACTUATORS

a. Purpose/Description:
- The program calculates the required actuator torque and speed, for the z-(vertical-) arm segment - based on parameters such as load mass, gear ratio, etc., for three specific DC motors.
- (Only the z-arm segment is considered, since it experiences the largest load - refer to Figure 4.7 in the dissertation.)

b. Inputs:
- Choice of a specific DC motor (three options) for the arm segments.
- Proposed speed reduction ratio between actuator and arm segment.

c. Outputs:
Available torque and speed for the chosen DC motor, compared with the required actuator torque and speed for the z-arm segment.

E.1.15 ARMSIM.M - DYNAMIC DESIGN AND ANALYSIS OF THE ROBOT ARM

a. Purpose/Description:
The program simulates the dynamic response of the arm segments, of the cartesian robot arm designed in the dissertation. (Non-linearities such as saturation, etc. are not considered.)

b. Inputs:
- Choice of arm segment to be simulated.

- Actuator parameters (for actuator chosen by means of ACTDES.M).
- Choice of input function (step input, sinusoidal input, or step input with sinusoidal input superimposed thereon).
- Characteristics of the chosen input function; and simulation time.
- Choice of output (e.g. actuator current, arm segment speed, arm segment position, etc.) to be simulated.

c. Outputs:
System response (time domain) of the chosen arm segment's chosen output.

E.2 TURBO-PASCAL PROGRAMS

E.2.1 GRAB.PAS - GRABBING AN IMAGE FRAME

a. Purpose/Description:
- The main purpose of this Turbo Pascal program is to "grab"/freeze an image displayed on the video monitor, with the purpose of reading the image frame into the computer's data storage unit.
- The program is also used for changing the resolution of a frozen image frame.
- The program is based on some *procedures* obtained with the OCULUS 200 frame grabber card (refer to Appendix A).

b. Inputs:
- Video images on the video monitor (displayed directly from a video camera, or from a video cassette recorder - refer to Figure A.1 in Appendix A.)
- Required resolution change.

c. Outputs:
- Frozen image frame on the monitor.
- Image frame with changed resolution.

E.2.2 VIDEOREA.PAS - TRANSFERRING AN IMAGE FROM THE VIDEO MONITOR TO THE DATA STORAGE UNIT

a. Purpose/Description:
- This Turbo Pascal program is used to transfer a frozen image frame from the video monitor, to the data storage unit.
- The program is based on *procedures* obtained with the OCULUS 200 frame grabber card.

b. Inputs:
Frozen image frame on the video monitor.

c. Outputs:
Image stored in 16 blocks on disk (see Figure A.2 for the data file format).

E.2.3 IMPROC.PAS - IMAGE PROCESSING

a. Purpose/Description:
- This Turbo Pascal program implements various image processing algorithms - including the Sobel edge enhancement operator.
- The program is based on *procedures* obtained with the OCULUS 200 frame grabber card.

b. Inputs:
- Image stored in 16 blocks on disk (refer to Figure A.2).
- Choice of operation to be executed.

c. Outputs:
- Display of the grey scale image read from disk.
- Binary image.
- Cursor on the graphics screen, with display of cursor position (relative to the screen's top left corner - in [pixels]).
- Edge enhanced image (Sobel operator).
- Edge enhanced image with all single points (noise) removed.
- Storage of image points on disk.

APPENDIX F

DESIGN OF THE MECHANICAL MANIPULATOR FOR A ROBOTIC MILKING MACHINE

F.1 INTRODUCTION

This appendix contains details of the mechanical design and construction of the manipulator subsystem of the milking robot. The designs are based on the different trade-offs presented in Chapter 4. Although this appendix contains well-known information, it is considered an important part of the dissertation, since it presents a formalized procedure for the design of a custom-made mechanical manipulator.

F.2 DESIGN OF THE ROBOT ARM

F.2.1 FRAME OF REFERENCE

The frame of reference defined in Section 4.2.4.1 for the robot arm, is the following:

a. Reference point: the geometrical centre of the robot arm's mounting point.

b. x-axis: horizontal; parallel with the length of the stall; and directed towards the stall's rear end.

c. y-axis: horizontal; and to the right (when looking from the robot arm towards the stall's rear end).

d. z-axis: vertical and downwards.

F.2.2 ROBOT ARM DESIGN CONSIDERATIONS

In Section 4.2.3, a cartesian robot arm was chosen as a suitable configuration for the milking robot; and Figure 4.7 shows a suitable cartesian arm for the milking robot. The following aspects are important for the construction of the robot arm as shown in Figure 4.7:

a. In the rest of this appendix, reference is made to the x-, y-, and z-arm segments. These names refer to the specific cartesian arm configuration in Figure 4.7, and its chosen frame of reference. The z-arm segment is the vertical one; the y-arm segment is the horizontal one attached to the z-arm segment; and the x-arm segment is the horizontal one to which the robot hand will be attached.

b. Each arm segment has a bearing block around it. The z-arm segment is stationary, with its bearing block moving up and down. The other two arm segments move within their bearing blocks. In order to minimize friction between the arm segment and the bearing block, the arm segment will run on roller bearing supported shafts, mounted within the bearing block - as shown in Figure F.3.

c. The actuators are mounted within sealed containers for protection against water, dust, and other adverse environmental conditions. (The y-arm segment's endpoint will fit over the x-arm segment's actuator - providing even better protection for this actuator.)

d. In order to ensure firm coupling between the arm segments and the bearing blocks, the arm segments are designed with square profiles.

e. In Section 4.2.1.1.b, it was shown that the milking robot's arm must reach 700 mm along the x-, the y-, and the z-axis (relative to its mounting position on the right hand side of the stall's floor).

F.2.3 MECHANICAL DESIGN OF THE ROBOT ARM

F.2.3.1 CONSIDERING THE ARM SEGMENTS AS SIMPLE BEAMS

A number of bending moments and torques will act on the arm, influencing its static behaviour. (In this analysis, disturbance forces - e.g. a cow leaning against the robot arm - are not considered.) The mechanical strength of the arm must be designed such that it will not only withstand these moments and torques; but that the deflections of the arm segments will not cause excessive errors in the robot hand's position. Each of the arm segments can be considered to be a simple beam, with its one end clamped, and the other end free. Each beam experiences concentrated forces, distributed forces, and torques acting on it. A generalized schematic representation of such a beam is shown in Figure F.1.

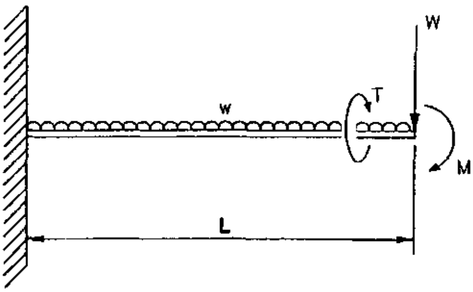


FIGURE F.1: Clamped beam subjected to a concentrated load, a distributed load, and two torques

The deflection of the free endpoint of a beam, such as the one shown in Figure F.1, due to the different loads on it, is given by equation (F.1) - refer to STEPHENS & BOTHMA (1978, pp.70 & 82):

a. Maximum deflection due to a concentrated load:
$d_c = (W.L^3)/(3.E.I_{xx})$ (F.1a)

b. Maximum deflection due to a distributed load:
$d_d = (w.L^4)/(8.E.I_{xx})$ (F.1b)

c. Maximum deflection due to a torque M, as shown in Figure F.1:
$d_m = (M.L^2)/(2.E.I_{xx})$ (F.1c)

d. Maximum twisting around the beam's long axis, due to a torque T, as shown in Figure F.1:
$\theta = (T/I_{zz}).(L/G)$ (F.1d)

with:-

- d: deflection of the beam, under different circumstances [m] - as defined in equations (F.1a) to (F.1c)
- E: Young's modulus (of elasticity) for the material of which the beam is constructed [Pa]
- G: shear modulus for the beam's material [Pa]
- I_{xx}: second area moment around the beam's horizontal short axis [m^4] (refer to Figure F.2)
- I_{zz}: second area moment around the beam's long axis [m^4]
- L: length of the beam [m]
- M: torque acting in the same plane as the beam's long axis [Nm]
- T: torque acting around the beam's long axis [Nm]
- w: distributed load on the beam [N/m]
- W: concentrated load on the beam [N]
- θ: twisting of beam due to torque acting around its long axis [rad]

It is important to design the arm segments with its masses as low as possible (from a cost point of view; as well as to minimize the arm's reaction time and the size of its actuators). It can be shown from equation (F.1) that the *strength-to-mass ratio of a hollow beam is* better than that of a solid beam. Therefore hollow beams will be used for the construction of the arm segments.

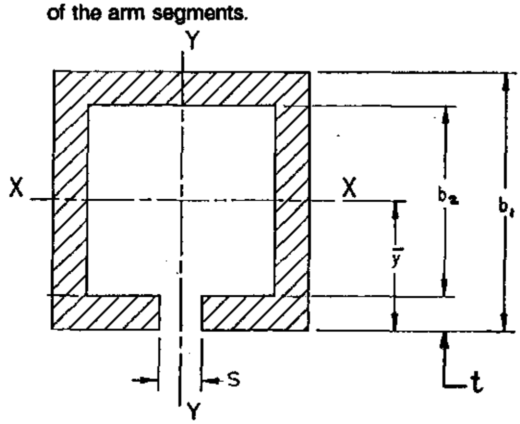


FIGURE F.2: Hollow square beam, with one slotted side

The analysis performed in Section 4.3.4 indicates that each of the arm segments will have to be slotted on one of its sides, and almost over its full length, in order to provide for power cables to reach the actuators. For the x- and the y-arm segment, the slots will be machined at the bottom of the beam, in order to prevent water and dirt from accumulating within the beam. (In order to prevent buckling of the beams, and to prevent the power cable from slipping out of the slots, the beams will be slotted to about 20 mm from its endpoints. The analysis which follows will however assume that the beams are slotted over their full lengths.)

For a hollow square beam as shown in Figure F.2, with outer dimension b_1, inner dimension b_2, wall thickness $t = (b_1 - b_2)/2$, and slot width S (in the middle of the beam's one side), the second area moments are calculated as follows: (STEPHENS & BOTHMA (1978, pp.40,41,48) and POPOV (1978, p.197))

$$I_{xx} = (b_1^4-b_2^4-S.t^3)/12 + (y_n-b_1/2)^2(b_1^2-b_2^2) - S.t.(y_n-t/2)^2 \quad \text{(F.2)}$$

$$I_{yy} = (b_1^4-b_2^4-t.S^3)/12 \quad \text{(F.3)}$$

$$I_{zz} = I_{xx} + I_{yy} \quad \text{(F.4)}$$

with:-

$$y_n = [0,5.b_1(b_1^2-b_2^2)-0,5.S.t^2]/[b_1^2-b_2^2-S.t] \quad \text{.....(F.5)}$$

F.2.3.2 DESIGN APPROACH

Different design approaches can be followed - e.g. the maximum allowable deflection, the outer dimension of the beam, and the loads can be specified, from which the beam's inner dimension can be determined; or the beam's dimensions can be specified, from which the deflection can be calculated. These calculations can be repeated iteratively until satisfying results are obtained. Appendix E contains the summary of a PC-MATLAB program ARMDES.M (consisting of a main program, plus three sub-programs), which was written to execute the following tasks:

a. To design the arm segments, based on the concentrated load at its endpoints; and on other chosen characteristics.

b. To calculate the deflections and twistings of the arm segments, according to equation (F.1).

c. To analyze the errors in the robot hand's x-, y-, and z-positions, due to the deflections and twistings of the arm segments.

The design is done for worst case conditions (i.e. maximum loads, and arm segments extended to their maximum lengths, etc.).

F.2.3.2.1 Inputs to program ARMDES.M

The program ARMDES.M starts by requesting the following inputs:

a. the maximum allowable deflection of the x-arm segment, due to the concentrated load on it;

b. the concentrated load on the x-arm segment's endpoint;

c. the suggested outer dimension of the arm segment.

d. the length of the arm segment;

e. the width of the slot in the arm segment;

f. a choice between aluminium and steel beams.

F.2.3.2.2 Deflection of the x-arm segment

The first sub-program (ARMDESX.M) uses the above inputs to determine the maximum inner dimension (b_2) of a hollow square beam, with its one end free, and its other end clamped. For the first part of the program, it is assumed that none of the beam's sides are slotted. Furthermore, in this first part of the program, the beam's own weight is not taken into account (because it is not yet known), but only the concentrated load at its endpoint. Under these conditions, (F.2) reduces to (F.6):

$$I_{xx} = (b_1^4-b_2^4)/12 \quad \text{(F.6)}$$

Consequently the beam's inner dimension is calculated from (F.7) - derived by substituting (F.6) into (F.1a):

$$b_2 = [b_1^4 - (4.W_x.L_x^3)/(E.d_x)]^{1/4} \quad \text{(F.7)}$$

With the value of b_2 calculated from (F.7) as a guideline, the program user is prompted to input a smaller (standard/commercially available) value for the inner dimension of the beam.

The next part of the program determines the deflection of a slotted beam, due to the concentrated load on its endpoint, and due to its own weight - by making use of (F.8). (The newly chosen inner dimension is used for these calculations.)

$$d_{x1} = d_{cx1} + d_{dx1} = (W_x.L_x^3)/(3.E.I_{xx}) + (w_x.L_x^4)/(8.E.I_{xx}) \quad .....(F.8)$$

This deflection of the x-arm segment, causes errors in the x- and the z-position of the robot hand. The z-position error is calculated as in (F.9); while the x-position error can be approximated - by making use of simple trigonometry - as in (F.10). (The signs of the error terms are in accordance with the frame of reference defined in Section F.2.1 above.)

$$z_{e1} = d_{x1} \quad (F.9)$$

$$x_{e1} = -(L_x - (L_x^2 - z_{e1}^2)^{1/2}) \quad (F.10)$$

F.2.3.2.3 Deflection and twisting of the y-arm segment

The second sub-program (ARMDESY.M) uses the same inner and outer dimensions for the y-arm segment, as those chosen for the x-arm segment. The deflection of the y-arm segment's endpoint, due to a concentrated load (the masses of everything beyond the y-arm segment's endpoint, lumped at this endpoint), and due to the y-arm segment's own weight, is first calculated. Secondly, the twisting of the y-arm segment, due to the torque generated by the x-arm segment, is calculated.

The program user is prompted for a value of the lumped load on the y-arm segment's endpoint, after which (F.1a) is used to determine the deflection due to a concentrated load. The distributed load, and consequent deflection are the same as those for the x-arm segment (because the same beam dimensions are used). The deflection of the y-arm segment causes errors in the y- and the z-position of the robot hand - calculated from (F.23) and (F.24):

$$z_{e2} = d_{y1} = (W_y.L_y^3)/(3.E.I_{xx}) + (w_y.L_y^4)/(8.E.I_{xx}) \quad (F.11)$$

$$y_{e2} = -(L_y - (L_y^2 - z_{e2}^2)^{1/2}) \quad (F.12)$$

The torque about the y-arm segment's long axis, due to concentrated load on the x-arm segment's endpoint, plus the weight of the x-arm segment is calculated from (F.13):

$$T_y = W_x.L_x + 0,5.w_x.L_x^2 \quad (F.13)$$

This torque causes the y-arm segment to twist - calculated from (F.1d). This angle of twist results in errors in the x- and the z-position of the robot hand - calculated from (F.14) and (F.15):

$$z_{e3} = d_{x2} = \theta.L_x = (T_y/I_{zz}).(L_y/G).L_x \quad (F.14)$$

$$x_{e3} = -(L_x - (L_x^2 - z_{e3}^2)^{1/2}) \quad (F.15)$$

F.2.3.2.4 Deflection of the z-arm segment

The third sub-program (ARMDESZ.M) uses the same inner and outer dimensions for the z-arm segment, as those chosen for the x-arm segment. The deflection of the z-arm segment's endpoint, due to the torque generated by the x-arm segment, and the torque generated by the y-arm segment, is calculated.

The torque on the z-arm segment, due to the concentrated load on the y-arm segment, and its own weight, is calculated by means of (F.16); while the torque on the z-arm segment due to the x-arm segment's loads, is calculated by means of (F.17):

$$T_{z1} = W_y.L_y + 0,5.w_y.L_y^2 \quad (F.16)$$

$$T_{z2} = T_y = W_x.L_x + 0,5.w_x.L_x^2 \quad (F.17)$$

The torque given by (F.16) causes a deflection d_{z1}, of the z-arm segment, resulting in a deflection of the y- arm segment. If the slot in the z-arm segment is in the wall under the actuator, d_{z1} is given by (F.18a); while (F.18b) is used if the slot is in one of the side walls. These deflections result in errors in the y- and the z-position of the robot hand - calculated from (F.19) and (F.20):

$$d_{z1} = T_{z1}.L_y^2/(2.E.I_{xx}) \quad (F.18a)$$

$$d_{z1} = T_{z1}.L_y^2/(2.E.I_{yy}) \quad (F.18b)$$

$$z_{e4} = d_{z1} + L_y - (L_y^2 - d_{z1}^2)^{1/2} \quad (F.19)$$

$$y_{e4} = (L_y^2 - d_{z1})^{1/2} - L_y + d_{z1} \quad (F.20)$$

The torque given by (F.17) causes a deflection d_{z2}, of the z-arm segment, resulting in a deflection of the x- arm segment. If the slot in the z-arm segment is in the wall under the actuator, d_{z1} is given by (F.21a); while (F.21b) is used if the slot is in one of the side walls. These deflections result in errors in the x- and the z-position of the robot hand - calculated from (F.22) and (F.23):

$$d_{z2} = T_{z2}.L_x^2/(2.E.I_{yy}) \quad \text{(F.21a)}$$

$$d_{z2} = T_{z2}.L_x^2/(2.E.I_{xx}) \quad \text{(F.21b)}$$

$$z_{e5} = d_{z2} + L_x - (L_x^2 - d_{z2}^2)^{1/2} \quad \text{(F.22)}$$

$$x_{e5} = (L_x^2 - d_{z2})^{1/2} - L_x + d_{z2} \quad \text{(F.23)}$$

(The above equations for the errors are derived from simple trigonometry.)

F.2.3.2.5 Calculation of total errors in the robot hand's x-, y- and z-positions

The total errors in the robot hand's x-, y- and z-positions are determined in the last part of the main program ARMDES.M, as the sums of the above error components:

$$x_e = x_{e1} + x_{e3} + x_{e5} \quad \text{(F.24)}$$

$$y_e = y_{e2} + y_{e4} \quad \text{(F.25)}$$

$$z_e = z_{e1} + z_{e2} + z_{e3} + z_{e4} + z_{e5} \quad \text{(F.26)}$$

F.2.3.3 CHOSEN ARM CHARACTERISTICS

The weight of an *Alfa Laval* teatcup plus its attached pipes was measured as being in the order of 10 N. In Section 4.2.1.1.b it was decided that the length of each arm segment shall be 700 mm. The following parameters are chosen or calculated in the sections as cross-referenced: (The iterative nature of the design is again evident from the information and the procedure used below.)

a. In order to provide for worst-case design, it is assumed that the x-arm segment must be designed for a concentrated load of W_x = 30 N at its endpoint.

b. It is decided that the deflection of the x-arm segment, due to the mass of the teatcup and the robot hand, shall be less than 0,5 mm.

c. It is decided that aluminium shall be used for constructing the arm segments (mainly because of its resistance to corrosion). For aluminium, the modulus of elasticity is $E = 69.10^9$ Pa; and the shear modulus is $G \approx 26.10^9$ Pa (ASHBY & JONES (1980, pp.30-31)). The density of aluminium is about 2700 kg/m^3 (IREMONGER (1982, p.26)).

d. The outer dimension of the hollow square beam is chosen as b_1 = 50 mm.

e. The mass of the bearing block (Section F.2.3.5 below) is approximately 0,7 kg; its weight is thus 7 N. The mass of each arm segment (Section F.2.3.4 below) is 1,65 kg. In Section F.3.2.3 below, the Inland RBE-501 DC Motor is chosen as a suitable actuator for the robot arm. In the data sheet its mass is specified as 0,119 kg. The concentrated weight on the y-arm segment's endpoint consists of the weights of the teatcup and hand (30 N); the x-arm segment (16,5 N); the x-axis bearing block (7 N); and the x-axis actuator (1,2 N). Therefore, $W_y \approx 55$ N.

F.2.3.4 ROBOT ARM DESIGN RESULTS

By utilising the PC-MATLAB program ARMDES.M, a cartesian arm for the milking robot (as shown in Figure 4.7), was designed with the following mechanical characteristics:

a. Type of material for arm segments: aluminium.

b. Reaching distance of each arm segment: 700 mm. (The arm segments can be constructed somewhat longer, to allow for slight overshoot due to the controller; and for part of the arm segment being covered by the bearing block. The strength calculations will not be influenced by this extra length, since it is assumed that the arm segments will not travel more than 700 mm however.)

c. Mass of each arm segment: 1,65 kg.

d. Profile of each arm segment: hollow beam, with outer dimension of 50 mm; and inner dimension of 40 mm. For the x- and y-arm segments, the bottom side has a 5 mm wide slot, over the arm segment's full length (except for the last 20 mm on each side). The z-arm segment is slotted similarly. It was found from the program ARMDES.M that the position of the z-arm segment's slot (i.e. in which wall of the beam) causes a variation of less than 5% in the total static error. This variation is negligible in the light of the approximations made. Therefore it is not important which side of the z-arm segment is slotted.

e. Static error of the robot hand's x-position (due to loads acting on arm segments): $x_e \approx 0{,}3$ mm.

f. Static error of the robot hand's y-position (due to loads acting on arm segments): $y_e \approx 0{,}5$ mm.

g. Static error of the robot hand's z-position (due to loads acting on arm segments): $z_e \approx 2{,}3$ mm.

The calculated error in the robot hand's z-position indicates that the hand will be slightly below the anticipated position. In Section 3.4.2 it was however pointed out that it is actually desirable to have the hand slightly below the teat's endpoint, before the hand starts moving upwards. The z-position error does therefore not cause any problems. The nett error in the x-y (horizontal) plane is less than 1 mm. Such an error is well within tolerable limits. Furthermore, the calculated values represent the worst case scenario, and is therefore accepted as it is.

F.2.3.5 BEARING BLOCKS

Figure F.3 shows the detail of the bearing blocks which act as interfaces between the arm segments. The main body of the bearing block consists of an aluminium block, with an outer dimension of 85 mm; wall thickness of 5 mm; and length 125 mm. On each side of the arm segment running through the bearing block, there are two aluminium shafts of 5 mm diameter, supported by roller bearings. Each bearing block thus contains 8 such shafts and 16 roller bearings. Since the density of aluminium is about 2700 kg/m^3 the calculated mass of a bearing block is in the order of 0,7 kg.

In order to adapt to the milking robot's hygiene requirements, sealed bearings will be used. Furthermore, pillow block type bearings will be used, in order to facilitate their attachment to the outer housing of the bearing block.

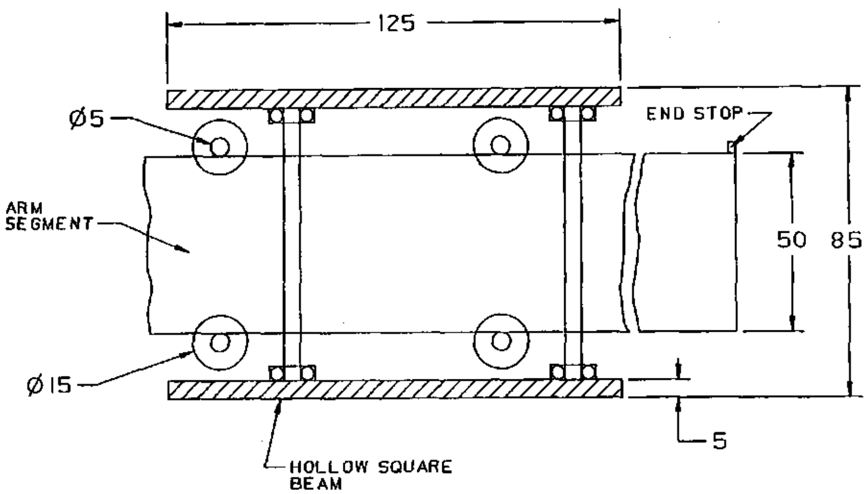


FIGURE F.3: Detail of the robot arm's bearing blocks

F.3 DESIGN OF THE ACTUATORS FOR THE ROBOT ARM

F.3.1 REACHING DISTANCE, SPEED, AND ACCELERATION

In this section a triangular speed curve is assumed for the three arm segments (the same for all three arm segments). From this speed curve, the bottom limit of the required actuator acceleration is calculated. This value will be used in the next section to derive the minimum torque which the actuators should be able to deliver. (Note that the acceleration calculated from the assumed speed curve, is only the bottom limit of this parameter. Ideally, the chosen actuators will be able to perform better than this value - resulting in a different top speed, reached earlier than that indicated in the speed curve, but still with the same average speed.) The reasoning behind choosing a triangular speed curve for design purposes, is as follows:

a. The mechanical time constant of a system like the robot arm is normally much larger than the electrical time constant. The armature inductance of small DC servo motors can often be neglected. If $sL_a \approx 0$ in the blockdiagram shown in Figure 4.17, it is evident that each segment/axis of the robot arm will approach the behaviour of a second order dynamic system.

b. It has already been decided that for robotic milking a cow's movements must be restricted in the stall - by making use of one of the mechanisms mentioned in Section 2.4.1. Ideally the cow will thus stand still, and each of the three segments of the robot arm will be subjected to a step input, as its position command signal. Depending on the characteristics of each arm segment and its controller, the response of each arm segment to a step input will be exponential.

c. Since arm segment speed is the time derivative of the arm segment position, the speed will also be an exponential function - starting at zero, then rising exponentially to a maximum, and then falling exponentially to zero again.

d. For each axis, the minimum actuator requirements (torque and speed) are dictated by the required travelling distance and by the available time for travelling. These requirements do not dictate a specific speed curve, but only a minimum average speed.

e. Although it is now known that for a position step input, the speed curve will first rise and then fall exponentially, the exact nature of this exponential response is not known. The exact nature of the response depends on the parameters of the system. As a first order approximation, a linearised (triangular) speed curve can be assumed for determining the minimum performance specifications for the actuator.

f. If the actuator designed by this approach does not meet the overall system requirements, the process can be repeated with another speed curve, based on the first iteration's results. (This represents the iterative nature of engineering design.)

In Section 4.2.1.1.b, it was shown that the milking robot's arm must reach at least 700 mm along the x-, the y-, and the z-axis (relative to the arm's mounting position on the right hand side of the stall's floor).

For design purposes, an average speed of at least 0,5 m/s is chosen for each of the robot's axes. This will allow each arm segment to travel its full 700 mm in less than 1,5 s.

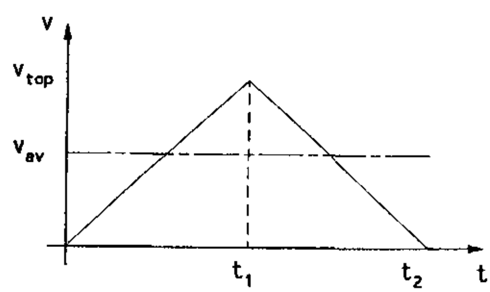


FIGURE F.4: Assumed speed curve for the robot arm segments

If a speed curve, such as that shown in Figure F.4, is assumed for the robot arm, then the acceleration and deceleration, and the top speed are calculated as shown below.

Calculation of the available travelling time:

Reaching distance: $s = 0,7$ m (F.27)

Average speed: $v_{av} = 0,5$ m/s (F.28)

Available travelling time: $t = s/v_{av} = 1,4$ s .....(F.29)

Lengths of time intervals:
$t_1 = 0,7$ s (F.30)
$(t_2 - t_1) = 0,7$ s (F.31)

Distance travelled during time interval $0 \le t \le t_1$ (half the total distance):
$s_1 = 0,35\ m$ (F.32)

Acceleration during the time interval $0 \le t \le t_1$:
Initial speed: $u_1 = 0$ (F.33)
$s_1 = u_1 t_1 + 0,5 a_1 t_1^2$
$0,35 = 0,245 a_1$ (F.34)
$=> \quad a_1 \approx 1,43\ m/s^2$ (F.35)

Acceleration during the time interval $t_1 < t \le t_2$:
$a_2 = -a_1$
$= -1,43\ m/s^2$ (F.36)

If the actuator's acceleration is $1,43\ m/s^2$, the arm segment's top speed will be:
$v_{top} = a_1 t_1$
$= 1\ m/s$ (F.37)

Summarized, the robot arm's motion parameters, for each of its three axes, are:

a. Reaching distance: $s = 0,7$ m (F.27)
b. Average speed: $v_{av} = 0,5$ m/s (F.28)
c. Top speed: $v_{top} = 1,0$ m/s (F.37)
b. Acceleration and deceleration (bottom limit): $a = 1,43\ m/s^2$ (F.36)

F.3.2 LOAD FORCES AND ACTUATOR TORQUE RATINGS

F.3.2.1 GENERAL EQUATION OF MOTION

The torques required from the robot arm's actuators must be sufficient to accelerate the load, and to overcome friction. Since the cartesian arm's three axes are orthogonal, there is zero coupling between the dynamics of the three axes (in the ideal case). Depending on the bearing blocks used for the physical coupling between the axes, the orthogonality of the three axes might be slightly distorted - causing minor cross-coupling between the dynamics of the three axes. These effects will however be neglected in the analysis.

From iterative design it was concluded that a speed reduction gearbox (the gear ratio is *defined as $n < 1$ for a reduction gearbox*) is required between the actuator and the load. (This is required in order to step up the actuator torque and to step down the actuator speed.) In Section 4.3.3 it was decided to use a pulley and cable mechanism, for converting the actuator's torque T (rotational quantity) to a force F (linear quantity) on the arm segment. For a pulley with radius r in such a set-up, the relationships between gearbox output rotation (θ_g) and motor/actuator output rotation (θ_m); and between gearbox output rotation (θ_g) and arm *segment linear movement* (s), are:

$$\theta_m = \theta_g / n \quad \text{(F.38)}$$

$$\theta_g = s/r \quad \text{(F.39)}$$

$$=> \quad \theta_m = s/(n.r) \quad \text{(F.40)}$$

The above three equations also apply for the relationships between the actuator and gearbox speeds, and accelerations. The general equation of motion for all three the robot's axes is:

$$\begin{aligned} T_m &= J_m(d^2\theta_m/dt^2) + B_m(d\theta_m/dt) + n.T_l \\ &= J_m(d^2\theta_m/dt^2) + B_m(d\theta_m/dt) + n.F_l.r \\ &= (J_m/(n.r) + n.r.M_l)a + (B_m/(n.r) + n.r.B_a)v \end{aligned} \quad \text{.....(F.41)}$$

with:-

a:	linear acceleration of the x-, y- or z-arm segment $[m/s^2]$
B_a:	linear viscous friction coefficient between the arm segment and the bearing block [N/(m/s)]
B_m:	*combined rotational viscous friction* coefficient of the actuator and the gearbox [Nm/(rad/s)]
F_l:	load force [N]
J_m:	combined moment of inertia of the actuator, the gearbox, and the pulley $[kg.m^2]$
M_l:	total load mass experienced by a specific arm segment [kg]
n:	gearbox ratio (n<1 for speed reduction)
r:	radius of the pulley [m]
T_l:	torque experienced by the actuator, due to the load force [Nm]
T_m:	torque generated by the actuator [Nm]
v:	speed of the arm segment [m/s]
$d^2\theta_m/dt^2$:	rotational acceleration of the actuator $[rad/s^2]$
$d\theta_m/dt$:	rotational speed of the actuator [rad/s]

F.3.2.2 ACTUATOR DESIGN APPROACH

The load masses as experienced by the three actuators are:

$$M_{lx} = M_t + M_h + M_{ax} \quad (F.42)$$

$$M_{ly} = M_t + M_h + M_{ax} + M_{bx} + M_{mx} + M_{ay} \quad .....(F.43)$$

$$M_{lz} = M_t + M_h + M_{ax} + M_{bx} + M_{mx} + M_{ay} + M_{by} + M_{my} + M_{bz} + M_{mz} \quad .....(F.44)$$

with:-

M_{ax}, M_{ay}:	masses of the x- and y-arm segments [kg]
M_{bx}, M_{by}, M_{bz}:	masses of the x-, y-, and z-bearing blocks [kg]
M_h:	mass of the robot hand [kg]
M_{lx}, M_{ly}, M_{lz}:	load masses along the x-, y-, and z-axis [kg]
M_{mx}, M_{my}, M_{mz}:	masses of the x-, y-, and z-actuators [kg]
M_t:	mass of the teatcup, and its pipes [kg]

Since the z-axis experiences the highest load mass, this axis is chosen for the actuator design. This design process is again very iterative. The approach followed is as follows:

a. Assume a value of 10 kg for the z-axis load (based on the masses already known from previous analysis, and on estimates for the actuator masses).

b. Calculate the required force in order to accelerate the load:

$$F_l = M_l.a = (10)(1,43) = 14,3 \text{ N} \quad (F.45)$$

c. Choose a drive pulley radius of 20 mm. The required torque on the drive pulley is then:

$$T_l = F_l.r = (14,3)(0,02) = 0,286 \text{ Nm} \quad (F.46)$$

d. The required top speed of the drive pulley (with radius r = 20 mm) is:

$$d\theta_l/dt = v_{top}/r = 1/0,02 = 50 \text{ rad/s} \quad (F.47)$$

e. The power output of the actuator is thus:

$$P = T_l\,(d\theta_l/dt) = (0,286)(50) = 14,3 \text{ W} \quad (F.48)$$

f. Assume that a speed reduction gearbox with an efficiency of 85% will be used as part of the transmission system. That implies that the actuator's output power must be at least 17 W.

g. Make use of DC servo motor catalogues to search for actuators which satisfy the above requirements, and verify their performance by means of the PC-MATLAB program ACTDES.M (refer to Appendix E for a program summary).

F.3.2.3 <u>ACTUATOR DESIGN</u>

Two groups of DC servo motors were investigated, namely the brushless motors manufactured by Inland Motor Kollmorgen Corporation, 501 First Street, Radford, Virginia 24141, U.S.A.; and permanent magnet MAXON DC motors manufactured by Interelectric AG, CH-6072 Sachseln, OW Switzerland.

Although the MAXON series included motors which seemed to meet the requirements, the mechanical time constants specified in the data sheets, indicated excessive viscous friction coefficients. Three motors of the INLAND series - namely the RBE-00402; RBE-00501; and RBE-00502 - were consequently investigated by means of the program ACTDES.M.

By trying different gear ratios (for speed reduction, and for increasing the load torque), the following results were obtained for the Inland RBE-00501 motor, driving the load through a gear ratio of n = 0,1 (i.e. a 10:1 reduction of motor speed).

a. From (F.47) the required motor top speed is:

$$N_{req} = (60/2\pi)(d\theta_l/dt)/n = (60/2\pi)(50)/0,1 \approx 4775 \text{ rpm} \quad (F.49)$$

b. From the motor's data sheet (INLAND MOTOR (1988, p.47)), the available motor top speed is:

$$N_{avail} = 4951 \text{ rpm} \quad (F.50)$$

c. From (F.46) the required motor torque is:

$$T_{req} = T_l.n = (0,286)(0,1) \approx 0,029 \text{ Nm} \quad (F.51)$$

d. From the motor's data sheet (INLAND

MOTOR (1988, p.47)), the available motor torque is:

$T_{avail} = 0,033$ Nm (F.52)

From the above analysis it was concluded that the Inland RBE-00501 DC servo motor, with a 10:1 reduction gearbox, and driving the arm segment through a cable and a pulley with radius of 20 mm, would be sufficient for the z-axis. Since the x- and the y-axis have lower load masses than the z-axis, the same type of actuator will also be sufficient for these axes.

The mass of this chosen actuator is 0,119 kg (from the data sheet). With this actuator mass taken into account, the mass of the z-axis load will be lower than the 10 kg assumed above. The chosen actuator will therefore definitely be able to meet its requirements.

F.4 DESIGN OF THE ROBOT HAND

F.4.1 FRAME OF REFERENCE FOR THE ROBOT HAND

In Section 4.4 it was decided to implement a robot hand without the ability for pitch, roll, or yaw movement. The hand must only be able to grasp a teatcup, hold it vertically, and let go of it. The robot hand can thus be considered to be an extension of the last arm segment, and it does therefore not require its own frame of reference.

F.4.2 SUMMARY OF REQUIRED ROBOT HAND CONFIGURATION

In Sections 4.4.1 to 4.4.5, a robot hand with the following characteristics was chosen as the most suitable configuration to satisfy the specific requirements defined for the milking robot:

a. A robot hand with two scissor-action fingers.

b. A robot hand utilizing the teatcup's mechanical construction to effect grasping.

c. A robot hand with an onboard actuator.

d. A robot hand utilizing a rotating actuator (DC servo motor), plus a cable and spring mechanism to open and close the fingers.

F.4.3 HAND CONSTRUCTION

Figure 4.15 contains a proposed configuration of a hand suitable for the milking robot.

The diameter of a typical teatcup is in the order of 50 mm. In order to allow a reasonable positioning tolerance, the maximum opening distance between the endpoints of the two fingers is chosen as 70 mm. The nominal distance which each finger tip must thus be able to move, can be derived from Figure 4.15 as being in the order of d_f = 15 mm. (This allows the finger tips to slightly enclose the teatcup.) Choose the following parameter values:

a. Radius of the pulley on the hand's actuator, r_{ph} = 10 mm;

b. Length of the finger segment from the tip to the pivot point, L_{f1} = 50 mm;

c. Length of the finger segment from the pivot point to the interaction point with the actuating rod, L_{f2} = 20 mm.

The required movement of the hand's actuator is then - from (F.53):

$$\begin{aligned}\theta_{mh} &= (L_{f2}/L_{f1}).(d_f/r_{ph}) \\ &= (20/50).(15/10) \\ &= 0,6 \text{ rad} \\ &\approx 35^\circ \end{aligned} \qquad (F.53)$$

F.4.4 ACTUATOR RATINGS FOR THE ROBOT HAND

The main constraint on the actuator is its size. An Inland RBE-00401 DC servo motor is chosen, with the following characteristics:

a. Supply voltage: 24 V;

b. Maximum continuous torque: 0,012 Nm;

c. Maximum continuous speed: 11950 rpm;

d. Peak torque: 0,101 Nm;

e. Diameter: 23,8 mm;

f. Length: 46,1 mm (motor body - 36,6 mm, output shaft - 9,5 mm);

g. Mass: 59,5 g;

h. Moment of inertia: $1,9 \times 10^{-7}$ kg.m^2;

i. Viscous damping coefficient: $8,4 \times 10^{-7}$ Nm/(rad/s).

F.4.5 ESTIMATION OF THE HAND'S MASS

An estimate of the robot hand's mass is made in this section. The hand - made from aluminium, with a density of 2700 kg/m^3 - has the following dimensions (refer to Figure 4.15) and consequent masses:

a. Two fingers: ((50 + 35) mm long x 10 mm x 10 mm)
$m_f = 2.(50.10^{-3} + 35.10^{-3}).(10.10^{-3})^2.2700$
$= 45,9$ g.

b. Actuating rod: (5 mm diameter x 45 mm long)

$m_{ra} = \pi.(2,5.10^{-3})^2.45.10^{-3}.2700$
$= 2,39$ g.

c. Actuator housing: (hollow square beam, 50 mm outer dimension; 5 mm wall thickness; 35 mm long)

$m_{ha} = ((50.10^{-3})^2-(40.10^{-3})^2).35.10^{-3}.2700$
$= 85,05$ g.

d. Two cover plates of actuator housing: (50 mm x 50 mm x 5 mm thick)
$m_{cp} = 2.(50.10^{-3})^2.5.10^{-3}.2700$
$= 67,5$ g.

e. Two lugs with pivot points for fingers: (20 mm long x 10 mm x 10 mm)

$m_{lh} = 2.20.10^{-3}.(10.10^{-3})^2.2700$
$= 10,8$ g.

f. Pulley: (20 mm diameter x 10 mm long)

$m_{ph} = \pi.(10.10^{-3})^2.10.10^{-3}.2700$
$= 8,48$ g.

g. Actuator:

$m_{mh} = 59,5$ g.

h. Spring plus diverse components:

$m_{sh} = 10$ g.

The hand's total mass is therefore: $m_h \approx 0,3$ kg.

F.5 CONCLUSIONS

In this appendix, the constructional details were derived for a suitable robot arm, actuators, and robot hand for a milking robot. Although the design results are derived from well-known principles, the appendix contains important guidelines with respect to a formalized procedure for the design of a custom-made manipulator. Implementation of the designed manipulator might show aspects which have not been adequately considered during the design process, but the results presented here form a baseline for the construction of a suitable mechanical manipulator for a milking robot.

APPENDIX G

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APPENDIX H

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CURRICULUM VITAE

Johan Gouws grew up on a dairy and maize farm, after he was born in Heidelberg, Transvaal, South Africa, on 14 November 1960. He completed a Bachelor of Engineering degree (Electrical and Electronic), at the Rand Afrikaans University, Johannesburg, South Africa, in June 1983. In May 1985 he obtained a Master of Engineering degree (Electrical and Electronic) (*cum laude*) - also at the Rand Afrikaans University. The latter was obtained (after part-time study) for research on control systems with more than one dominant nonlinearty in the control loops. Besides numerous merit bursaries and prizes, he was also the first recipient of the Chancellor's Gold Medal (for academic achievement), at the Rand Afrikaans University, in 1986. During his undergraduate years he had been involved in the management committees of various students' and other organizations.

He and his wife (a mechanical engineer) have their own company, working as consultants for a number of clients in South Africa. They cover a wide spectrum of engineering design, system engineering, and project management activities. He was previously employed by a consulting engineering company in South Africa; and he has been involved in the development of a large number of engineering systems, including electrical and hydraulic servo controllers, multi-variable control systems, automated animal feeding systems, and high-precision position and speed sensors. His responsibilities during these developments included electronic and servo system design and implementation; system modelling; system simulation; system integration, test, and evaluation; feasibility studies; company management; contracting; and project management.

From 1982 to 1985 he was a part-time lecturer at the Technikon Witwatersrand, Johannesburg, South Africa - responsible for courses in Electronics, Electrical Machines, and Automatic Control Systems. During 1988 and 1989 he was also a part-time lecturer at the Rand Afrikaans University, Johannesburg, South Africa - responsible for courses in Automatic Control Systems.