Farm Technology Group

BSc thesis Farm Technology

Sensors and Safety Systems

The design of a safety system on the spraying vehicles that will spray in strawberry fields and orchards

Rob Ormel

July 2012

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The design of a safety system on the spraying vehicles that will spray in strawberry fields and orchards

Name Course	:	Bachelorafsluiting Agrotechnologie
Number	:	FTE-80812
Study Load	:	12 credits
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Preface

During the Bachelor Agrotechnology many different fields of work of the agrotechnology has come by and many opportunities were given to exploit these fields. My field of interest is the technological side of arable farming. During the winter of 2012 I heard that PRI Wageningen was developing an autonomous spraying vehicle. After several conversations with Jan Willem Hofstee about a thesis subject this project came forward. There was no safety system for the autonomous spraying vehicle present and my thesis would make the first start for this system. In front of you lies the report in which the multiple sensors and the safety system are described and discussed. This thesis is the final part of my study program BSc Agrotechnology at Wageningen University, Wageningen.

I want to thank my supervisors Jan Willem Hofstee and Ard Nieuwenhuizen for their supervision on this thesis. They helped me with the difficulties that I encountered during this thesis.

Wageningen, Netherlands, July 2012

Rob Ormel

Summary

Plant Research International (PRI) is developing autonomous vehicles for spraying in strawberry fields and orchards. The safety of people and animals and other subjects in the surroundings of the vehicle has to be secured. Also the vehicle itself has to be protected for damage during its performance. The purpose of this thesis is to give an overview of existing sensors and safety systems on autonomous vehicles and how these systems can be used for the autonomous spraying vehicles.
The environment of the spraying vehicle is described. The different cultivation systems of orchards and strawberry field are discussed. It is important to know in which environment the spraying vehicle and thus the safety system has to perform. The characteristics of the spraying vehicle are given. The potential obstacles that the vehicle can encounter in the field are mentioned. To categorize these obstacles a model is developed. This model makes the distinction between obstacles with fixed placement (one fixed place) and dynamic obstacles (several places). Only dynamic obstacles are of interest for the safety system, because fixed obstacles can be programmed into the software as 'No-Go areas'. The main advantage is that these fixed obstacles do not have to be detected regularly by the safety system. Still the safety system must be capable to detect these obstacles when the vehicle drives into these areas by accident. The dynamic obstacles are divided in obstacles that form a hazard and obstacles that don't form a hazard for the vehicle. The safety system must comply with the policy 'Guaranteed Safety' (Kelly *et al.,* 1998). With this definition the sensors are tested on four different requirements, namely guaranteed response, guaranteed throughput, guaranteed detection and guaranteed localization. The sensors that are assessed for the safety system are: 2D laser scanner, 3D laser scanner, radar, ultrasonic sensors, camera and a TOF camera. All these sensors comply with these requirements, except for the radar system. Not enough data information was available to assess this sensor. Some sensors are more suitable for this application than others. But one sensor only is not enough to reach sufficient detection rates and accuracy of the system. Multiple sensors are needed to accomplish this. Data fusion will form an important role in the safety system. Multiple architectures are available to design the data fusion. Also multiple techniques are available to fuse the data together. The Kalman filter and the particle filter have the most potential as fusion technique for the safety system. Still the fusion architecture must be chosen in such way that the sensor data is used in the best possible way. The high-level control of the safety system must be done by a state machine. This is a powerful and very usable for the safety system. It can also easily be combined with the navigation system. At the end of the thesis the placement of the sensors is discussed. This placement is done to achieve the highest detection rate. The 2D laser scanner is mounted at the front of the vehicle at 0.75m from the ground surface. This height must be made adjustable with the height of the spray boom. The 3D laser scanner is also mounted at the front of the vehicle, but then at half the height of the vehicle. At this height the scanning pattern has no influence in the performance of the scanner in the range of that scanning pattern. Radar is not mentioned in the placement, because this sensor first have to be tested in practice to assess what the best place is. The ultrasonic sensors are placed at the out-and-outer places of the vehicle. This means at the end of the spray boom, cabin of the vehicle and at the front of the vehicle. The camera is mounted on the cabin. The TOF camera is placed at the cabin and at the front of the vehicle. Also three combinations of sensor types are proposed. Combination one is the 2D laser scanner combined with a camera. Combination two consist of a 3D laser scanner, a camera and ultrasonic sensors. The third combination consist of a TOF camera, 2D laser scanner and ultrasonic sensors. Combination one is proposed as the best combination to be tested.

Contents

1 Introduction

1.1 Present situation

Autonomous vehicles are still not a common phenomenon in the agricultural business. This development is now going on and many companies are working on the development of such vehicles. In the United States the 'DARPA Grand Challenge' was held three times, in which cars had to be able to autonomously drive a pre-set route through the desert and urban area. So there are autonomous vehicles developed throughout the years. These vehicles have different kind of sensors to be aware of the direct surrounding of the vehicle. Sensors like laser scanners, camera's and ultrasonic sensors are applied for the purpose of navigation and obstacle detection.

Plant Research International (PRI) is developing an autonomous vehicle for spraying in strawberry fields and orchards. The safety of people and animals and other subjects in the surroundings of the vehicle has to be secured. Also the vehicle itself has to be protected for damage during its operation. To secure the safety of people, animals and the vehicle itself, people are always present during the performance of the vehicle. There are different 'Stop-buttons' placed on the spraying vehicle that is developed by PRI. These 'Stop-buttons' can be used by the people that are present in the surrounding of the vehicle to stop its operation.

1.2 Desired situation

The spraying vehicle will operate autonomously. No people are necessary to in the surrounding of the vehicle to guaranteed a safe operation. Instead of people in the surrounding that detect obstacles the safety system will detect these obstacles and act according to the situation. The detection will be done by sensors who will cover the required space in the surrounding of the vehicle. The safety system itself will determine what action is appropriate according to the situation. Examples of possible actions are stopping, continuing driving and evasion manoeuvres. The safety of the vehicle and obstacles in the surrounding is guaranteed.

1.3 Problem definition

There is no overall safety system available that can be applied on the spraying vehicle that will spray in strawberry fields and orchards.

1.4 Objectives

The goal of my thesis is to give a proposal how the safety system must be applied on the spraying vehicle. The proposal will consist of sensors that must be applied, the placement of these sensors and the high-level control of the safety system.

1.5 Research questions

The main research question of this thesis is:

- How must the safety system be applied on the spraying vehicle?

From the main research question the following sub questions are deducted:

1. How does the environment look like in the strawberry fields and orchards? What are the characteristics of the spraying vehicle?
2. What are the requirements of the safety system in these fields? What can be expected of the safety system and of it surrounding?
3. What are the existing sensor to detect people, animals, obstacles and other threats?
4. What are the existing safety systems? How do they combine with the existing sensors?

5. How should the sensors be placed on the vehicle to maximize the detection rate of obstacles by the sensors? Which combinations of sensors are possible and give an high detection rate?

1.6 Demarcation

The focus of the thesis will mainly be the literature study that I will perform. The theoretical background of the different sensors and safety systems will be discussed. There is no time for testing the different sensors to evaluate their capabilities. Recommendations will be made how to test the different sensors on their capabilities.

1.7 Report structure

In Chapter 2 the environment of the spraying vehicle and the characteristics of the spraying vehicle itself are described. Possible obstacles in the environment are mentioned and these obstacles are put into a model to categorize them. In Chapter 3 the requirements of the safety system are stated and the requirements that are required for the sensors are discussed. These requirements are discussed for several different types of sensors in Chapter 4 and explained if the sensors comply with these requirements. Chapter 5 discussed the existing system and how this system must be applied on the spraying vehicle. In Chapter 6 the placement of the sensors on the spraying vehicle is proposed. Also three combinations of sensors are proposed and explained why this combination is made. Chapter 7 and 8 are respectively the discussion and conclusion of the main research question. In Chapter 9 the recommendations for further research are given.

2 Environment description

The spraying vehicle is meant to spray in two different fields, namely an strawberry field and an orchard. It is important to know in what environment the vehicle is operating when you design a safety system for the spraying vehicle. It is also important to known what the possible obstacles could be that the vehicle will encounter. When you know in which environment the safety system must operate and which obstacles must be detected the sensors and system can be designed specifically for that task. These obstacles will be listed and categorised in a model that will be developed in this section. The spraying vehicle itself will be introduced and the characteristics of the vehicle given.

2.1 Strawberry field

Strawberry is a fruit that can be cultivated in greenhouses on substrate and in the outdoor environment in the field. The spraying vehicle that is developed will be spraying in the outdoor field. Strawberry plants are planted in rows in which the intrarow distance is between 30 and 45 cm. The interrow distance in the bed is 60 cm. The distance between the most outer rows of two beds are 90 cm. The bed itself is 150 cm wide. A schematic overview is given in Figure 1.

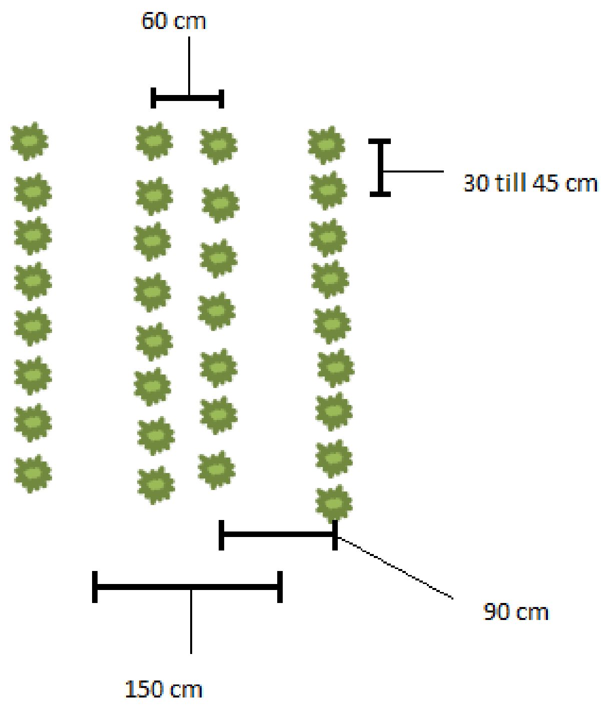


Figure 1: Schematic overview of an strawberry growing bed

To clarify the layout of the field even more an image of an real strawberry field is shown in Figure 2.

Figure 2: Image of an strawberry field (http://www.bredavandaag.nl/fotoalbums/weer/aardbeienveld)

2.2 Orchard

Different kinds of fruits, for example apples, pears, plums and cherry, are cultivated in orchards. The spraying vehicle will also be designed to spray the trees in an orchard. An orchard is a collection of trees in which the fruit grows. The main focus lies on the cultivation of apples and pears, because 85% of the orchards are cultivated for apples and pears (CBS, 2011). There are many different cultivation systems that are used in the cultivation of fruits. Below the most common system are discussed.

2.2.1 Spill system

In this system the trees are standing in multiple rows in the field. These rows have an interrow distance between 3.20 and 3.50 m. This depends on the choice of the grower. The trees have an intrarow distance of 1.50 m in the rows itself. The trees are slow growing trees (spills) that are planted in a close range to each other. In the beginning years the trees are supported by a pole that is placed next to it. The branches of the trees are supported by lines that are mounted on the poles. When the trees are full of fruit the branches are supported by these lines, to prevent possible breaking of the braches itself. The spill system can be seen in Figure 3.

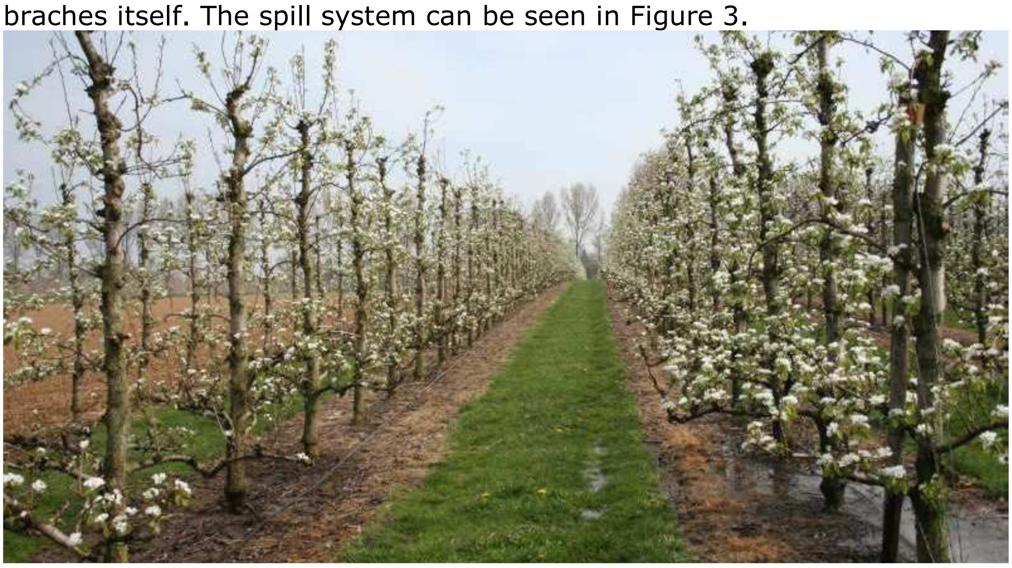


Figure 3: Spill system (Scheerlinck 2008)

2.2.2 V-hedge system

In the cultivation of pears the V-hedge system is more and more a common system because of the high yield per hectare. An example of a V-hedge system can be seen in Figure 4. The fruit trees are planted in the same rows as in all other systems, but they are forced to grow in a pre-set way, the V-shape. As the young trees are planted they are pruned in the shape of a V. Then they are strapped to a V-shape to grow. The interrow distance are between 3.20m and 3.50m. The intrarow distance is 1.0m. The space between the two 'legs' is held free of branches. The main advantage is that the sunlight can reach the pears very easily, so a greater yield is reached. The main disadvantage is that this system is more expensive than the spill system, because of the intensive pruning of the trees and the different plant technique (Reinhoudt, 1986).

Figure 4: V-hedge system (http://fruit.paginamarkt.nl/rss/401242.html)

2.2.3 Drapeau system

In the Drapeau system the trees are planted in an angle of 45°. This angle is in the row direction, as can be seen in Figure 5. The growing of the trees can easily be controlled, because of this angled growth (Scheerlinck, 2008). The heads of the trees are cut off. Every tree consist of six growing branches that are shaped in a V-shape. The main advantage of this is the same as can be seen in the V-hedge system. The sunlight can better reach the fruit that is hanging in the branches. The interrow distance is between 3.20 and 3.50 m. The intrarow distance between the trees is 1.75 m. This larger distance is due to the angled position of the trees.


Figure 5: The Drapeau system (Scheerlinck 2008)

2.3 Characteristics spraying vehicle

To determine if a sensor is suitable for the safety system the sensor must comply to the requirements. To do so, some characteristics of the spraying vehicle must be known. The dimensions of the tractor are given in Figure 6. The tractor that is used in the strawberry field is a New Holland Boomer 3045.

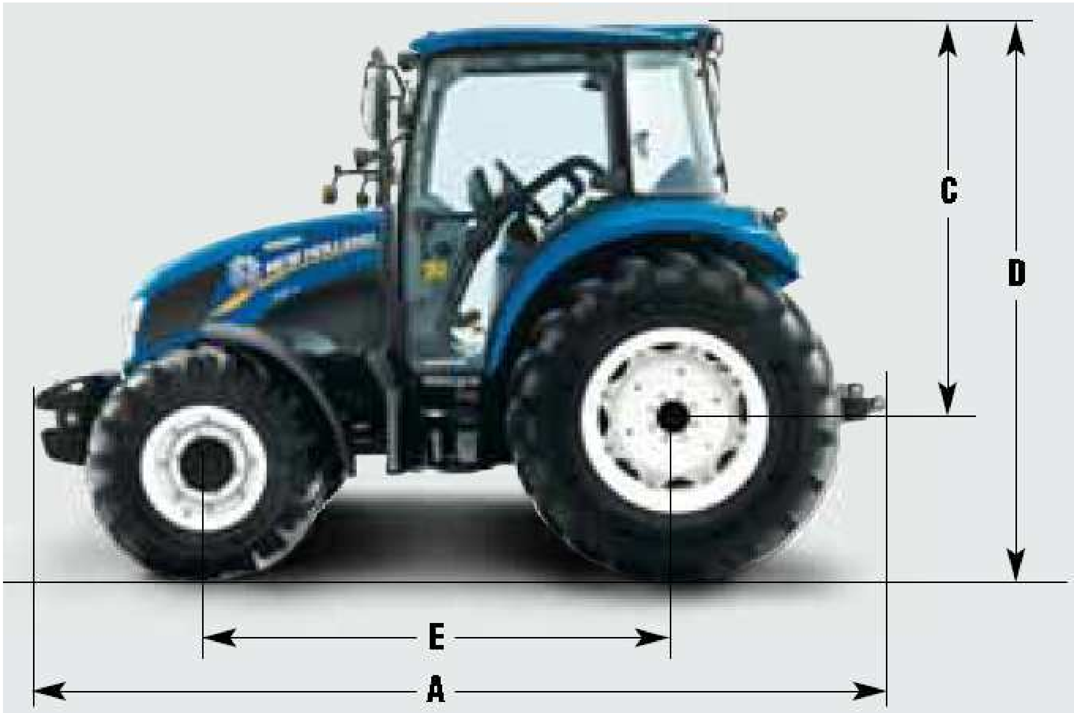


Figure 6: Dimensions of the tractor (New Holland 110001/NLO, 2012)

The tractor that is displayed in Figure 6 is not the Boomer 3045, but the image is used to give a better view of the dimensions of the tractor. The dimensions of the Boomer are:
A = 3.43m
C = 1.73m
D = 2.30m
E = 1.87m
Width = 1.82 m
The clearance underneath the tractor is 0.32m. (New Holland 80017/NLO, 2012)

The sprayer that will be used in the strawberry field is the Sensispray-Horti and can be seen in Figure 7. The dimensions of the sprayer are:
Width boom = 4.82 m
Height = 2.5 m
The height of the sprayer from the ground surface is depending on the actual position of the rear hitch links and the attachment construction of the sprayer.

Figure 7: Sensispray-Horti strawberry sprayer (Nieuwenhuizen, 2012)

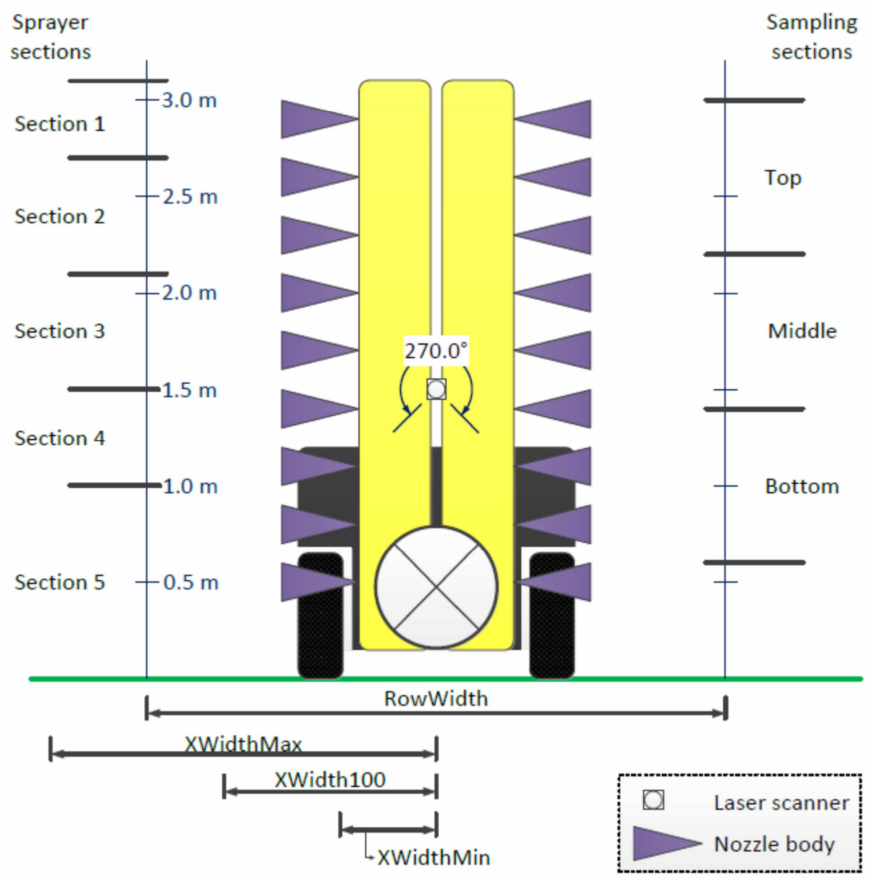


Figure 8: KWH D-1000 V-3.2 orchard sprayer (Sijbrandij, 2012)

The Boomer 3045 is not suitable to be used for the spraying activity in an orchard because this tractor is to large. For this purpose a Fendt 207V is used to perform the spraying activity. For this tractor the same notation will be used as in Figure 6.
A = 3.58m
C = 1.70m
D = 2.36m
E = 2.16m
Width = 1.16m
Clearance underneath the tractor is 0.3m. (AGCO GmbH, 2012)

The basis of the sprayer in the orchard is the KWH D-1000 V-3.2. This sprayer is adjusted for its task and can be seen in Figure 8. The dimensions of the sprayer are:
Width = 1.50m
Height = 3.20m (Sijbrandij, 2012).

2.4 Model

The purpose is to make a model in which all different obstacles can be placed under a specific category. With this model it is possible to categorise all obstacles that are known already and new obstacles that can be present in these environments in the coming future. Because of the big variety in which obstacles can be present in the fields the categorisation is hard to make.
In the strawberry field and the orchard the spraying vehicle will face different kinds of obstacles. These obstacles are of big importance for the spraying vehicle. There are big obstacles that can damage the spraying vehicle, but also small obstacles that don't damage the vehicle. The vehicle that is used makes the distinction for an object to become an obstacle for the vehicle or not. A tank for example has a higher obstacle tolerance than a quad. The size of an obstacle is due to the variety not an appropriate

characteristic to distinguish the obstacles. They can be placed in different categories in a model at the same time.
An important characteristic of an obstacle is the placement. The distinction is made between fixed placement (one fixed place) or dynamic placement (different places). The placement of a human and animal is dynamic. They can move across the field and be present in every spot in the environment. A tree for example cannot. When two objects collide with each other collision damage can occur. Collision damage is the financial damage that will occur when the spraying vehicle collide with the obstacle. This damage is the damage that could occur on the spraying vehicle, but also on the obstacle. The following costs are included in the damage value:

- Valuation costs
- Material costs
- Labour costs
- Temporally replacement costs

The model to categorize the obstacles is presented in Figure 9. In the first decision moment the distinction is made between fixed obstacles and dynamic obstacles. The fixed obstacles are not separated in any categories. The reason is that the safety systems will deal with these obstacles in a specific way. This will be described in the section 'Requirements of the safety system'. Because they are treated in a different way the categorisation in damage value does not add any value to the safety system. The dynamic obstacles are separated in different categories after they are assessed if they are a hazard for the spaying vehicle. There are four different categories for the obstacles that are assessed as a hazard. The categories are low costs, Medium low costs, Medium costs and High costs. The price indications are given in the boxes. The meaning of total loss is in two ways. It can be that the spraying vehicle is damage in such way that it cannot be repaired and it has to be replaced. The other way is that the obstacle is lost for a higher amount of damage value than the lower categories of € 50.000. For the obstacles that are assessed as no hazard for the spraying vehicle the categorisation is a bit different. The damage value scale is a little smaller, because obstacles that are not a hazard for the spraying vehicle are obstacles that give a lower damage value. Only the obstacles self can be damaged. The category 'Humans' is a different category due to the importance. Humans have an prominent place above all other obstacles. At all circumstances collisions with humans have to be avoided. Because it are living and unique organisms it are the most vital obstacles.

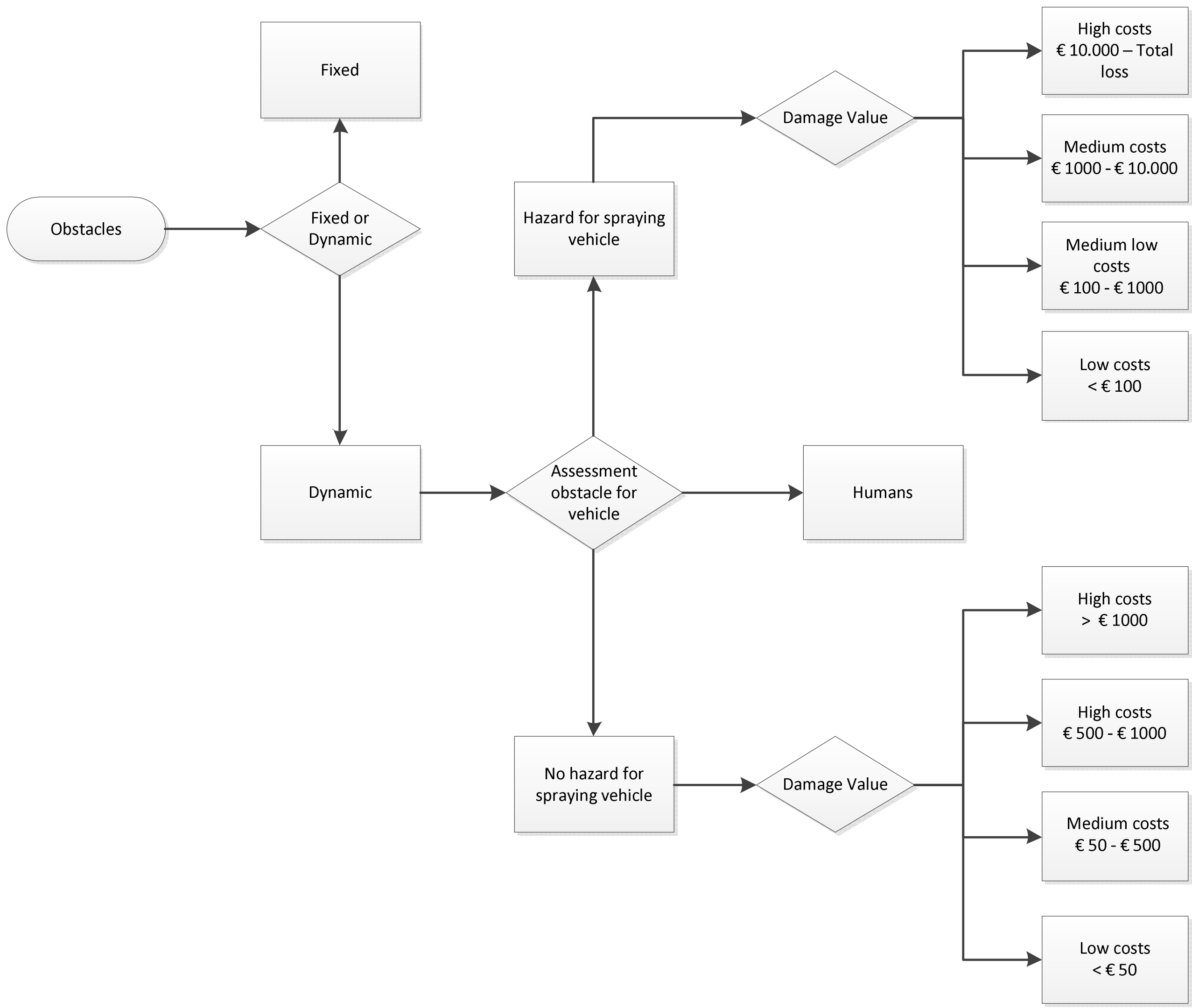


Figure 9: Model to categorize the possible obstacles in the field

2.4.1 Possible Obstacles Strawberry field

As in Figure 2 can be seen, the strawberry field has places were no obstacles are present. The plants are growing straight in their growing bed and the driving paths are clear of obstacles. Of course this is not always the case. As in Figure 2 can be seen there are also obstacles present in the driving paths of some beds. For instance the irrigation pipes with multiple sprinklers mounted on the pipes. In Table 1 a list of obstacles and their placement is given for a strawberry field.

Table 1: Possible obstacles in and around a strawberry field

Obstacle	Placement
Human	Dynamic
Large animal	Dynamic
Small animals	Dynamic
Irrigation Pipes	Fixed and Dynamic
Sprinklers	Fixed and Dynamic
Well	Fixed
Pole	Fixed and Dynamic
Fence	Fixed
Tree	Fixed

Fallen Branches	Dynamic
Hanging Branches	Dynamic
Bush	Fixed
Ditch	Fixed
Hole	Dynamic
Spade	Dynamic
Tractor	Dynamic
Machinery	Fixed and Dynamic
Cradle	Dynamic

The special place of the Human in this list is already discussed. Animals are obstacles that act different from the other objects. They move in time and can avoid the spraying vehicle. But collision are still possible. Large animals are animals in which an collision will result in a higher damage value. For example a cow. Examples of small animals are rats, rabbits or moles. The damage value will be a lot lower than of large animals.

2.4.2 Possible Obstacles in Orchard

The environment in orchards is full of potential obstacles that can cause problems for the spraying vehicle. An overview of all different obstacles is given in Table 2.

Table 2: Possible obstacles in an orchard

Obstacle	**Placement**
Human	Dynamic
Large animals	Dynamic
Small animals	Dynamic
Irrigation Pipes	Fixed and Dynamic
Sprinklers	Fixed and Dynamic
Well	Fixed
Pole	Fixed and Dynamic
Fence	Fixed
Tree	Fixed
Fallen Branches	Dynamic
Hanging Branches	Dynamic
Bush	Fixed
Ditch	Fixed
Hole	Dynamic
Spade	Dynamic
Tractor	Dynamic
Machinery	Fixed and Dynamic
Cradle	Dynamic
Lines	Fixed
V-shape skeleton	Fixed and Dynamic

An orchard is one big collection of trees that are possible obstacles. These obstacles have an fixed placement in the orchard. Navigation of the spraying vehicle through the orchard is a very important aspect to avoid collision with the fruit trees. Also the chance to hit branches that are hanging at the tree or did fall off is quit big. In an orchard equipment to support the trees are a common phenomenon. Examples are different lines, poles and skeletons in specific forms. These skeletons are placed at the same place as the trees are standing and also form a possible obstacle for the spraying vehicle.

2.5 Categorisation of obstacles

The differences between the obstacles that can be present in the two environments are small. Some specific objects are used in an orchard, like skeletons for the growing of the trees. Due to these small differences the categorisation of the obstacles will be done once and in one model. First the categorisation of fixed obstacles is shown here.

Fixed obstacles:

- Irrigation pipes
- Sprinklers
- Well
- Pole
- Fence
- Tree
- Bush
- Ditch
- Machinery
- Lines
- Skeleton

The second step is the categorisation of the dynamic obstacles. This is done in Figure 10. Some obstacles are mentioned in both in the enumeration of the fixed obstacles, Figure 10 and Figure 11. These obstacles can be present in a fixed form in the field, but also as an dynamic obstacle. Irrigation pipes for example are placed in the field at fixed places. But during the growing season they can be moved by external forces and then they will be categorised as an dynamic obstacle. At that point they are presents as a dynamic obstacle.

High costs € 10.000 - Total loss	• Large animals • Tractor • Machinery • Tree
Medium costs € 1.000 - € 10.000	• Hanging Branches
Medium low costs € 100 - €1.000	• Fallen Branches • Skeleton
Low costs < € 100	• Pole • Fence • Spade • Hole

Figure 10: Categorisation of Dynamic obstacles that form a hazard

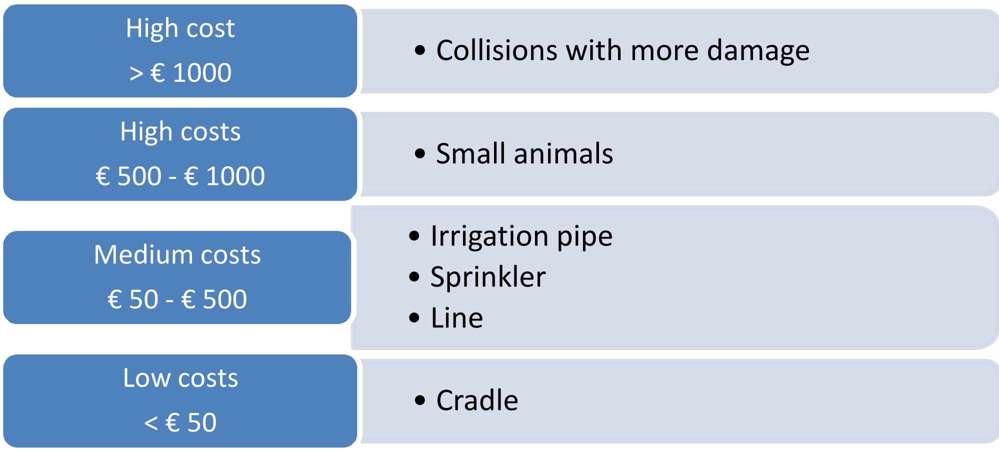


Figure 11: Categorisation of Dynamic obstacles that don't form a hazard

2.6 Discussion

The model presented in Figure 9 is an approximation to categorise the different obstacles. The model can be seen as arbitrary in the approach of the obstacles. At first the same obstacles can be seen as fixed obstacles and dynamic obstacles. This could be a sign that the model is not appropriate for this purpose, but it is useful in the practical sense. The assessment whether an obstacle is a hazard for the vehicle or not can be made in an arbitrary way. At last it is very difficult to make an estimation of the damage value in a collision with obstacle and vehicle. The damage value is depending on that many variables that every collision that may occur has to be evaluated on the costs. An accurate damage value for a collision is not possible to give. Therefore the numbers that are given in this model are estimations of the damage value. Colliding with an obstacle with a high damage value will automatically mean that there is a big hazard involved. Small damage value means a small hazard for the vehicle or the obstacle.

3 Requirements of the safety system

The safety system that will be mounted on the spraying vehicle must have capabilities with respect to detection of obstacles and further actions after the detection. But also from the environment of the spraying vehicle we can expect some actions to prevent collisions. In this chapter an outline of the requirements of recognition will be given. Also the possibilities of the further actions will be provided.

3.1 Assumptions

Before the requirements of the safety system are described two important assumptions are made. One with respect to the navigation system of the spraying vehicle and one with respect to the obstacles for which the safety system is designed.

3.1.1 Navigation

The spraying vehicle will have different systems to operate properly. The two main systems of interest for this thesis are the safety system and the navigation system. The navigation system will be responsible for the driving and navigation of the vehicle over the field. A connection has to be made between the two systems, because the safety system will not navigate the vehicle during a situation in which an obstacle is involved. The safety system will control the navigation system and tell what the navigation system has to do. It is important to realize that these two tasks are handled by two different systems, but that the safety system will control the navigation system in these situations.

3.1.2 Obstacles

In the previous chapter the obstacles were discussed and put in different categories: dynamic and fixed obstacles. The safety system will be designed for the dynamic obstacles. In the rest of the thesis the focus is on the dynamic obstacles, unless mentioned otherwise. For the fixed obstacles another approach of detection will be used. The fixed obstacles have one fixed place where they occur in the field that can be specified in coordinates. This is a very handy characteristic for an obstacle, because the detection of these obstacles is not required any more. When the location of the obstacle is known and fixed the navigation system can be programmed in such way that the spraying vehicle will avoid these places. The main advantages is that the safety system does not have to process these objects multiple times. It makes it easier for the safety system to aim itself only to the obstacles that are unpredictably present in the environment. In the navigation systems the so called 'No-Go-areas' have to be programmed. The spraying vehicle is not allowed to drive in these No-Go-areas at any circumstances. When the spraying vehicle is not driving in the area of fixed obstacles there is no chance of a collision. It is very important that the navigation systems is properly programmed for these No-Go-areas. Also the list of these areas has to be update when new fixed obstacles are added to the environment of the spraying vehicle. In this way the No-Go-areas can be adjusted and the safety of the vehicle and these objects is secured. When the navigation system fails and the spraying vehicle will drive into a No-Go-area the safety system will be able to detect the fixed obstacles. Collision will be prevented. Furthermore we assume that the field in which the spraying vehicle is driving is flat and so no negative obstacles will be present. Negative obstacles are obstacle that are placed underneath the ground surface. Examples of negative obstacles are gaps and ditches.

3.2 Guaranteed Safety

Any vehicle which attempts to navigate autonomously in the presence of unknown obstacles must exhibit performance that satisfies a basic set of requirements. If this vehicle is performing on the highest level of autonomously driving the control system must have a so called ‘Policy of Guaranteed Safety’ (Kelly *et al.*, 1998). This policy can be split in two different approaches. The first one is that the terrain in which the vehicle is navigating is not navigable and that the system then has to prove that the contrary is the case. The system has to prove that there are no obstacles in the navigation route. The second approach is the other way around. The vehicle makes the assumptions that the navigation route is navigable and free of obstacles unless the systems proofs the contrary. Kelly *et al.,* (1998) states that in more complex environments the first approach has to be used, because this is a more robust approach that offers more safety. However the environment in which the spraying vehicle will drive is not complex if you look to the standards of Kelly. The strawberry field and the orchard are relatively closed terrains and multiple obstacles are already known. These environments are, to a certain extent, quite controllable. Due to these characteristics of the environment the choice is made to design the safety system in the second approach. The policy of guaranteed safety can be separated in four different requirements of the safety system (Kelly *et al.*, 1998):

- Guaranteed response
- Guaranteed throughput
- Guaranteed detection
- Guaranteed localization

In the next sections the meaning of these requirements and how they could be applied on the spraying vehicle will be discussed.

3.2.1 Guaranteed Response

With guaranteed response is meant that the vehicle must have the time to response once the obstacle is detected. The response time is the time that the systems needs to produce a response on the changing environment. In the case of the spraying vehicle the obstacle will not be avoided, but the vehicle will stop for the obstacle. The response distance $L_{response}$ is defined as

$$L_{response} = v_{vehicle} \, * \, t_{response} \qquad (3.1)$$

with speed $v_{vehicle}$ and response time $t_{response}$. This is the distance that the vehicle needs to response to the changing environment. The response time includes the following times:

$$t_{response} = t_{sensing} + t_{detection} + t_{planning} + t_{commanding} + t_{actuator} + t_{vehicle} \qquad (3.2)$$

The response time is the overall time that is needed to act. For our use this response time can be divided in two different times of interest. First, the time needed to create the reaction will be defined as $t_{reaction}$. Second, the time to maneuver the vehicle will be defined as the maneuver time $t_{maneuver}$.

$$t_{reaction} = t_{sensing} + t_{detection} + t_{planning} + t_{commanding} + t_{actuator} \qquad (3.3)$$

$$t_{maneuver} = t_{vehicle} \qquad (3.4)$$

We can normalize this distance to have a clue how the vehicle is performing in comparising with other vehicles. The normalized response time expresses response distance in scale-independent terms. It shows the capacity of any vehicle to response relative to its own size. If the number is large the vehicle capacity to respond is low in this scale-independent term. To calculate the normalized response time $\sigma_{response}$ equation 3.5 is used.

$$\sigma_{response} = \frac{v_{vehicle} \cdot t_{response}}{L_{wheelbase}} \qquad (3.5)$$

To perform the response to an obstacle the response distance has to be smaller than the sensor lookahead distance Y_L. This is defined as the distance between the vehicle and the point of minimal view of the sensor. The response ratio $\rho_{response}$ must be smaller than 1 to comply to this.

$$\rho_{response} = \frac{v_{vehicle} \cdot t_{response}}{Y_L} \quad (3.6)$$

When the response ratio is bigger than 1 the response distance will be larger than the actual distance between the obstacle and the vehicle.

3.2.2 Guaranteed Throughput

The guaranteed throughput is a very important requirement of the system. With the guaranteed throughput is meant that the safety systems must have the capability to update its model of the environment of the vehicle at a rate that is commensurate with its speed. This means that the time interval of the sensor measurement must be adapted to its speed. When the time interval of measurements is too low the system will miss changes in the environment and thus obstacles. This can be expressed in the throughput ratio $\rho_{throughput}$

$$\rho_{throughput} = \frac{v_{vehicle} \cdot \Delta t_{measurement}}{Y_F} \quad (3.7)$$

where $v_{vehicle}$ is the speed of the vehicel, $\Delta t_{measurement}$ the time interval of measurements and Y_F the sensor field of view. This ratio must be kept less than unity, because a bigger ratio means that the $\Delta t_{measurement}$ is too large. For example, for a camera that is used for measurements the time between two images has to be small enough to cover the entire travelled distance during the time that these two images are taken.

3.2.3 Guaranteed Detection

Obstacles that are present in the environment have to be detected by the safety system before they can become a hazard for the spraying vehicle or the obstacle itself. There has to be a guaranteed detection of these dynamic obstacles. The place is dynamic and not known. These obstacles will alter in place and time. The threshold level to detect the obstacles has to be the potential hazard for both the vehicle and the obstacle. This threshold level can be determined by the acuity ratio ρ_{acuity}

$$\rho_{acuity} = \frac{S_r}{L} \quad (3.8)$$

with S_r the spatial resolution of the sensor pixel footprint and the wheelbase L of the vehicle. The idea behind this formula is that the smallest obstacle that can be resolved must be less than the smallest size of an obstacle that can become a hazard. A large vehicle is more robust to obstacles than a small vehicle. The larger vehicle has to cope with bigger obstacles. The smaller obstacles are of less importance for this vehicle. A practical system must always assume that there are no man-made or natural hazards that are smaller than some practical resolution limit. This will be called the smooth terrain assumption. The acuity ratio must be kept smaller than one-half.

3.2.4 Guaranteed Localisation

To give an appropriate action on the presence of an obstacle the location of the object with respect to the vehicle must be known. To do so, the accuracy of the perception has to be high enough, or the other way around, the error of the perception $\varepsilon_{perception}$ has to be sufficiently small.

$$\varepsilon_{perception} \rightarrow 0 \quad (3.9)$$

Completely zero will be impossible, that is why $\varepsilon_{perception}$ tends to zero. Kelly *et al.* (1998) stated that "sufficiently accurately" depends on the size of the vehicle and the spacing between obstacles in some average, worst-case, or other useful sense. This is stated in the fidelity ratio $\rho_{fidelity}$

$$\rho_{fidelity} = \frac{ds}{d_{obstacles} - W} \tag{3.10}$$

where ds is the error between the planned route of the vehicle and the actual performed route, $d_{obstacle}$ for the distance between two obstacles and W the width of the vehicle. The fidelity ratio must be kept below one-half to meet the requirement to hold the margin of the error for driving exactly between two separated obstacles. This margin is half the difference between the obstacle spacing and the vehicle dimension (Kelly *et al.*, 1998).

3.3 Safety range

The guaranteed response consist of stopping with driving when an obstacle is detected in the specific safety range. This range is depending on the driving direction and the speed of the vehicle. An obstacle will only be a hazard when it is positioned in the driving direction of the spraying vehicle. The safety range is only pointed in this direction. Obstacles that are detected at the side or in the opposite direction of the driving direction will have no effect on the safety system or the safety range. The speed is a dependent variable for the safety range. The spraying vehicle will be driving with a constant speed $v_{vehicle}$ in a direction.

$$v_{vehicle}(t) = v_0 \tag{3.11}$$

When the vehicle must stop for an obstacle it will be performing a retardant motion; the vehicle will stop driving. The speed of the vehicle $v_{vehicle}$ will become

$$v_{vehicle}(t) = v + a \cdot t^2 \tag{3.12}$$

in which a is the acceleration and t is time. The acceleration is the braking capacity of the vehicle and will be negative in this equation. The safety range of the vehicle must be large enough to stop in time. When the safety system detects an obstacles it first needs the time $t_{reaction}$ to give the actuators the signal what to do. In $t_{reaction}$ the vehicle will drive on with the same speed and will cover a certain distance before the vehicle will begin to brake. The time that it takes to stop is dependent on $v_{vehicle}$.

$$t_{maneuvre} = \frac{v_0}{a} \tag{3.13}$$

The distance that is travelled in motion with an constant speed and a motion with an accelerating speed is given in equations 3.12 and 3.13.

$$s = v_0 \cdot t \tag{3.14}$$

$$s = v_0 * t + \frac{1}{2} a \cdot t \tag{3.15}$$

The distance that the vehicle will travel $S_{vehicle}$ is calculated by combining the reaction time and the manoeuvre time in the distance equation of the safety range.

$$s_{vehicle} = (t_{reaction} + t_{maneuvre}) \cdot v_0 + \frac{1}{2} a \cdot t_{maneuvre}^2 \tag{3.16}$$

a is negative, because it is the breaking capacity. $s_{vehicle}$ is the minimal distance between the start of the safety range and the vehicle. With this distance the vehicle has enough time to stop for an upcoming obstacle. In an orchard the safety range has to be adjusted to the orchard system that is used. When the vehicle is driving through the orchard the trees may not be seen as an obstacle for which it has to stop. Only when the driving direction is towards a tree and the distance between the vehicle and the tree becomes too small, the tree becomes an obstacle and should be detected. Then it has to stand in the safety range.

3.4 Further actions

When an obstacle is detected and the spraying vehicle has stopped, the vehicle has dealt with the hazard. After a certain period of time the spraying vehicle has to scan the environment again to check if the obstacle is still present in its safety range. If the obstacle is still present the vehicle cannot proceed with driving. When the obstacle is not present any more the vehicle can continue its path and proceed with its action. The checking of obstacles can be repeated a specific number of times with a certain time interval. When the obstacles is still present in the safety range after these check-ups the safety system must give a distress call to the manager of the vehicle. This manager can check the safety range for obstacles and remove these obstacles out of the safety range. When this is done the manager must have the option to reset the vehicles safety and navigation system to let the vehicle proceed with its action. The model for this is given in Figure 12.

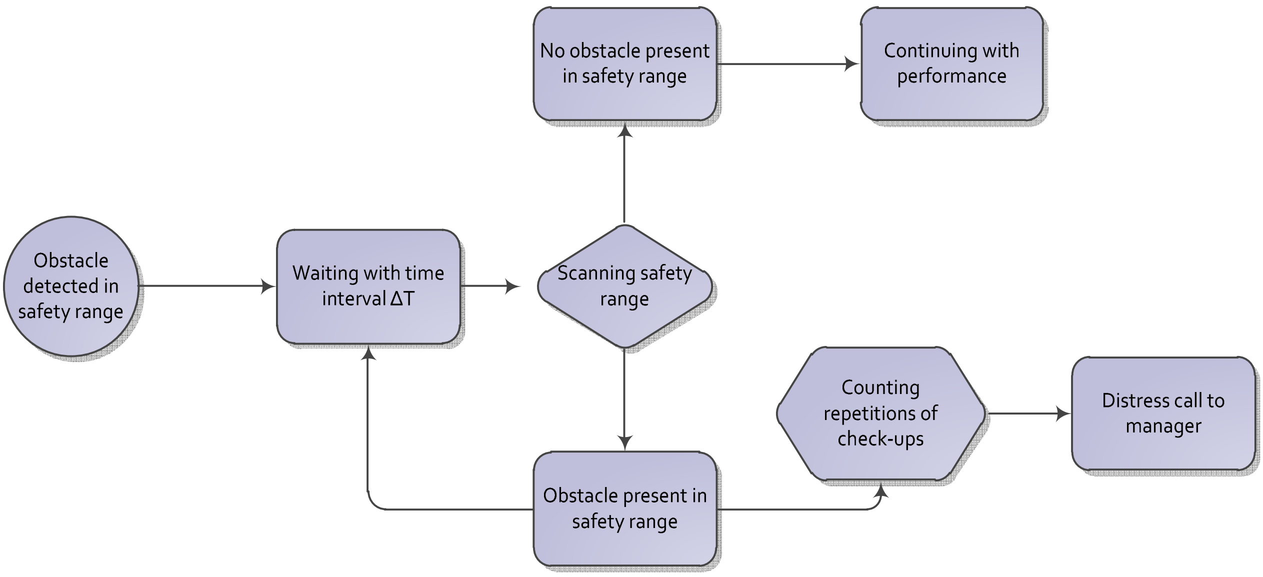


Figure 12: Action model for the spraying vehicle

3.5 Expectation of surrounding

The field in which the vehicle will drive must be cleared of any unnecessary objects. Hanging branches for example can be removed before the spraying vehicle will be performing in the field. Also potential hazards like bumps and holes have to be flattened. The environment of the spraying vehicle consists of different elements. We can expect some behaviour of these obstacles. It is likely that wild animals will not stay in the surrounding of the spraying vehicle because of the unnatural appearance of the vehicle. The sound, colour and movement for example are not natural and will scare the animals away. Domesticated animals perform the same behaviour as wild animals and be scared by the vehicle. Horses for example are will be scared of the vehicle. Cows and sheep are curious animals and will perform other behaviour. They are curious about the vehicle and will move towards the vehicle, exceptions excluded.
In the past machines and vehicles were not designed to operate on itself without human supervision. They were not build to protect the people who were working and standing in the surrounding of the machine. People were expected to keep good notion about the

hazards that they encountered and that they had to deal with it by being cautious. Also intervention of humans in the operation of the machine was normal. Nowadays, the machine and vehicle must be designed in such a way that it protects the people who are standing in the surrounding. The machine also needs to be able to operate without human supervision. The question raise what we can expect of the humans who will encounter the spraying vehicle. The expectation is that if they are not familiar with the vehicle, they want to have a look and can end up in the safety range of the vehicle. To prevent that the people will step into the safety range signs to warn the people that an autonomous vehicle is driving on the field can be placed and that a certain distance between them and the vehicle is required. Some obstacles that are mentioned in Table 1 and Table 2 are equipment that is left behind accidentally. We cannot do anything about it, except instructing the employees in the field that they check the field after they performed their work on the field.

3.6 Discussion

The assumptions that no negative obstacles will be present in the field is justified. For the owner of the orchard or the strawberry field it is very practical to have a field without unexpected holes. The chance that negative obstacles will appear suddenly in the Dutch situation is very small.

The reaction time $t_{reaction}$ of the safety system is dependent on the processing capacity of the computer. This hardware must be chosen in such way that this time is sufficiently small to create the reaction in time.

The acuity ratio is dependent of the wheelbase of the vehicle. Making the threshold level of hazard for the detection of obstacles depended on the wheelbase of the spraying vehicle is not a strong point. The wheelbase is a size and this is a very subjective characteristic to determine the hazard level. Small obstacles can cause damage with the result that the spraying vehicle has to stop its performance. To check if the proposed sensors are suitable for the safety system this parameter will still be used. That the acuity ratio must stay under one-half is also arbitrary. For every vehicle this value is different, because the vehicle determines with what obstacles it can deal with.

The fidelity ratio stands when the vehicle needs to make an avoiding manoeuvre. The spraying vehicle will not make an avoiding manoeuvre, so the fidelity ratio is not of interest in this topic. But the localisation of the obstacles is important for us. The spraying vehicle needs to know the distance between the obstacle and itself to make the decision to keep driving or to stop. The equation stated in 3.9 will be used instead of the fidelity ratio.

4 Existing sensors

To detect the obstacles in the safety range of the spraying vehicle sensors are needed to do that job. In this chapter an overview of different sensors that can be used are given. The characteristics of the sensor with respect to the sensors requirements is discussed.

4.1 Calculations

All the described sensors have to comply with the requirements of the safety system that are mentioned in the previous chapter. To do so, we will calculate the requirements of the guaranteed safety. First the assumptions that are needed for the calculations are discussed.

4.1.1 Assumptions

The speed of the spraying vehicle is variable and is depended on spraying conditions. For spraying in the strawberry field the speed of the vehicle is 6.0 $km \cdot h^{-1}$ (1.67 $m \cdot s^{-1}$) (Nieuwenhuizen, 2012). In the orchard the spraying vehicle will be driving with a speed between zero and 8.5 $km \cdot h^{-1}$ (2.37 $m \cdot s^{-1}$) (Sijbrandij, 2012). To be sure that the speed of the vehicle is not the bottleneck of the safety system the maximum speed is set to 9 $km \cdot h^{-1}$ (2.5 $m \cdot s^{-1}$). All calculations are done with this maximum speed.
The breaking capacity of both tractors are not known at this moment. The minimal breaking capacity in the Dutch law of the both tractors is 3.1 $m \cdot s^{-2}$ (SWOV, 2010). In practice this value will be bigger than 3.1 $m \cdot s^{-2}$.
The reaction time of a human is one second. We can assume that the safety system can perform this task faster. However, this depends on the processing capacity of the computer. In the calculations the value of one second is taken, because this is the maximum threshold level if the computer is compared with the reaction time of humans.

4.1.2 Requirements

First the safety range must be calculated for the spraying vehicle. This is automatically the same as the sensors lookahead distance Y_L. All sensors have to comply with this safety range.

Safety Range:

$$t_{maneuvre} = \frac{v_0}{a} = \frac{2.5}{3.1} = 0.81\ s$$

$$t_{reaction} = 1\ s$$

$$s_{vehicle} = (t_{reaction} + t_{maneuvre}) \cdot v_0 + \frac{1}{2} a \cdot t_{maneuvre}^2 = 5.54\ m$$

Guaranteed Response:

$$\rho_{response} = \frac{v_{vehicle} \cdot t_{response}}{Y_L} = 0.82$$

The speed of the vehicle (2.5 $m \cdot s^{-1}$), the $t_{response}$ (1.81 s) and the lookahead distance Y_L (5.54 m) are known. If the sensor complies with the lookahead distance the sensor complies with the guaranteed response.

Guaranteed Throughput:

$$\rho_{throughput} = \frac{v_{vehicle} \cdot \Delta t_{measurement}}{Y_F} < 1$$

The guaranteed throughput is different for every sensor. This is depending on the time interval of the measurements and the sensor field of view. These two characteristics of the sensor will be checked to see if the sensor complies with the guaranteed throughput.

Guaranteed Detection:

$$\rho_{acuity} = \frac{S_r}{L} < \frac{1}{2}$$

The guaranteed response depends on S_r, the sensor resolution of the pixel footprint. The wheelbase L of the vehicle is known.

Guaranteed Localisation: $\varepsilon_{perception} = \frac{Perceived\ location}{Actual\ location} \rightarrow 0$

The guaranteed localisation of the object depends on the error between the perceived location of the object and the actual location. This error is non-dimensional and can be found by testing the sensor. In the demarcation of this thesis it is described that there no sensors will be tested in practice. Because of this limitation the guaranteed localisation cannot be determined. Some examples will be given of sensors with the theoretical accuracy provided by the manufacturer. This theoretical accuracy will differ from the actual accuracy of the sensor in working conditions on the vehicle.

4.2 Laser scanner

A laser scanner is based on the principle of Time of Flight (TOF). The laser scanner sends a laser beam out to the environment and this beam reflects on a surface. The reflected laser beam returns to the laser scanner and it will calculates the TOF of the beam. Because the beam travels with the fixed speed of light ($300 \cdot 10^6$ $m \cdot s^{-1}$) the distance between the laser scanner and the reflection surface can be calculated. In this section we make the distinction between 2D laser scanners and 3D laser scanners.

4.2.1 2D laser scanner

The 2D laser scanners are widely used within the mobile robotics community and have been applied to object following and obstacle avoidance (Martinez *et al*., 1998). 2D-laser scanner sends out the laser beam to a rotating mirror. This rotating mirror makes it possible to spread the beam in the two dimensional way. This results in a fan-shaped scan pattern (Ye *et al*., 2002) in which the objects are detected. In Figure 13 an example of a laser scanner is shown. In this case the Sick LMS 200 is schematically drawn. The fan-shaped scan pattern is shown in Figure 14.

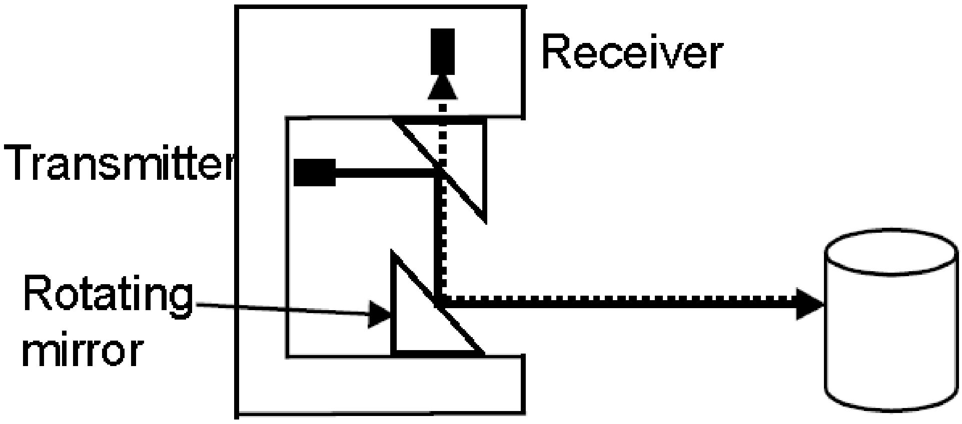


Figure 13: Example of a 2D-laser scanner (Ye *et al*., 2002)

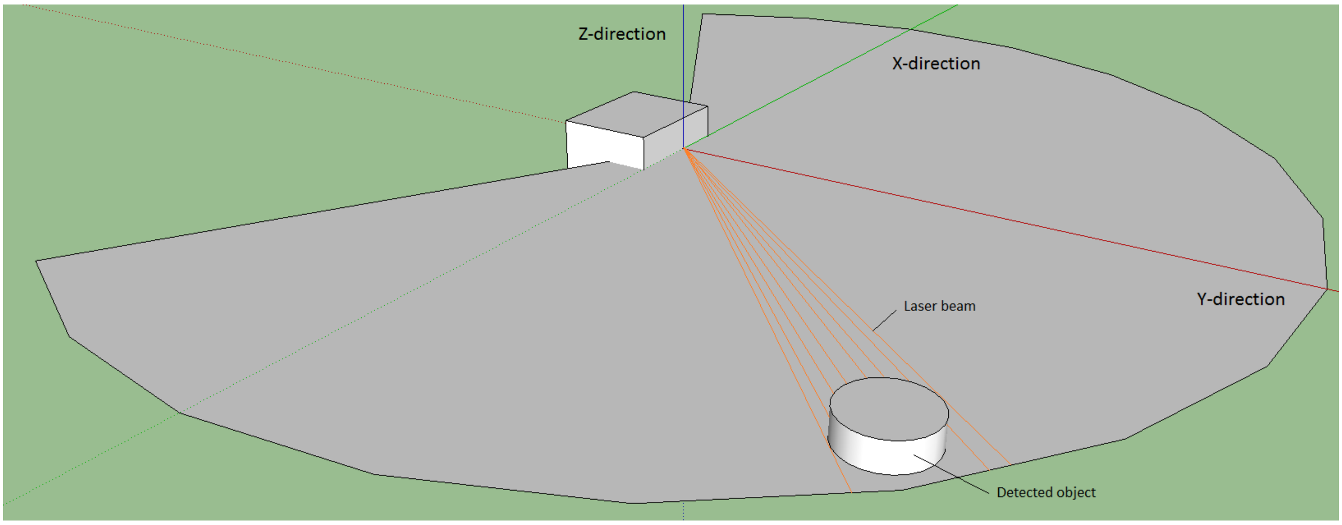


Figure 14: Fan shape of the scanner

As in Figure 13 can be seen the laser beam is transmitted by the transmitter and reflected by the rotating mirror to get the 2D scanning plane. The rotating mirror rotates with a very high speed, in the case of the Sick LMS 200 4500 rev·min^{-1} (75 rev·s^{-1}). The beam is reflected by the surface of the cylinder and is reflected by the rotating mirror to the receiver. The TOF is then known and the distance between the laser scanner and the cylinder can be calculated. After scanning the environment the data about the distance must be processed to valuable information. The output of this process is the distance between the laser scanner and the detected obstacle. The outcome of the laser scanner must comply with the requirements of the sensors.
Guaranteed Response: To comply with this requirement the sensor lookahead must be larger than 5.54 m. There are laser scanner who can scan the environment for 20 m and more (SICK, 2009).
Guaranteed Throughput: The time interval of a laser scanner is very small. Like mentioned before a laser scanner scans the range multiple times per second (Ye *et al.*, 2002). For the calculations the time interval of measurements is taken 20 ms (SICK, 2009).

$$\rho_{throughput} = \frac{v_{vehicle} \cdot \Delta t_{measurement}}{Y_F} = \frac{2.5 \cdot 0.02}{5.54} = 0.009$$

The laser scanner complies with the guaranteed throughput.
Guaranteed Detection: The spatial resolution of the laser scanner is very small. In this calculation we will take the value of 8 mm (SICK, 2009). For the Boomer 3045 the acuity ratio will be

$$\rho_{acuity} = \frac{S_r}{L} = \frac{0.008}{1.87} = 0.004$$

For the Fendt 207V the acuity ratio becomes

$$\rho_{acuity} = \frac{S_r}{L} = \frac{0.008}{2.16} = 0.004$$

For both the Boomer and the Fendt the acuity ratio stays below one-half.
Guaranteed Localisation: In the case of the SICK laser scanner the systematic error is 30 mm (SICK, 2009).

4.2.2 3D laser scanner

The 2D laser scanner scans in a horizontal plane parallel to the ground surface the distance in two dimensions; the so called X and Y directions (see Figure 14). The 3D laser scanner works with the same scanning principle as the 2D, but then the scanning plane is moved in the third direction; Z, the height direction. It does not make the movement in the Z direction itself, but will rotate over the X-axes within a certain angle. The laser scanner will rotate over a certain axes, not necessary the Z-axes. The 3D laser scanner can be used for collision avoidance on mobile robots. For the application on the spraying vehicle three types of scanning are suitable, namely the pitching scan, the yawing scan and the rolling scan (see Figure 15). The rolling scan has got the most measurement points in the area of interest, directly in front of the vehicle (Wulf *et al.,* 2003). The scanning type influences the performance of the laser scanner, because the scanning dots can be concentrated more to a specific area. That is the reason that the scanning principle is discussed here.

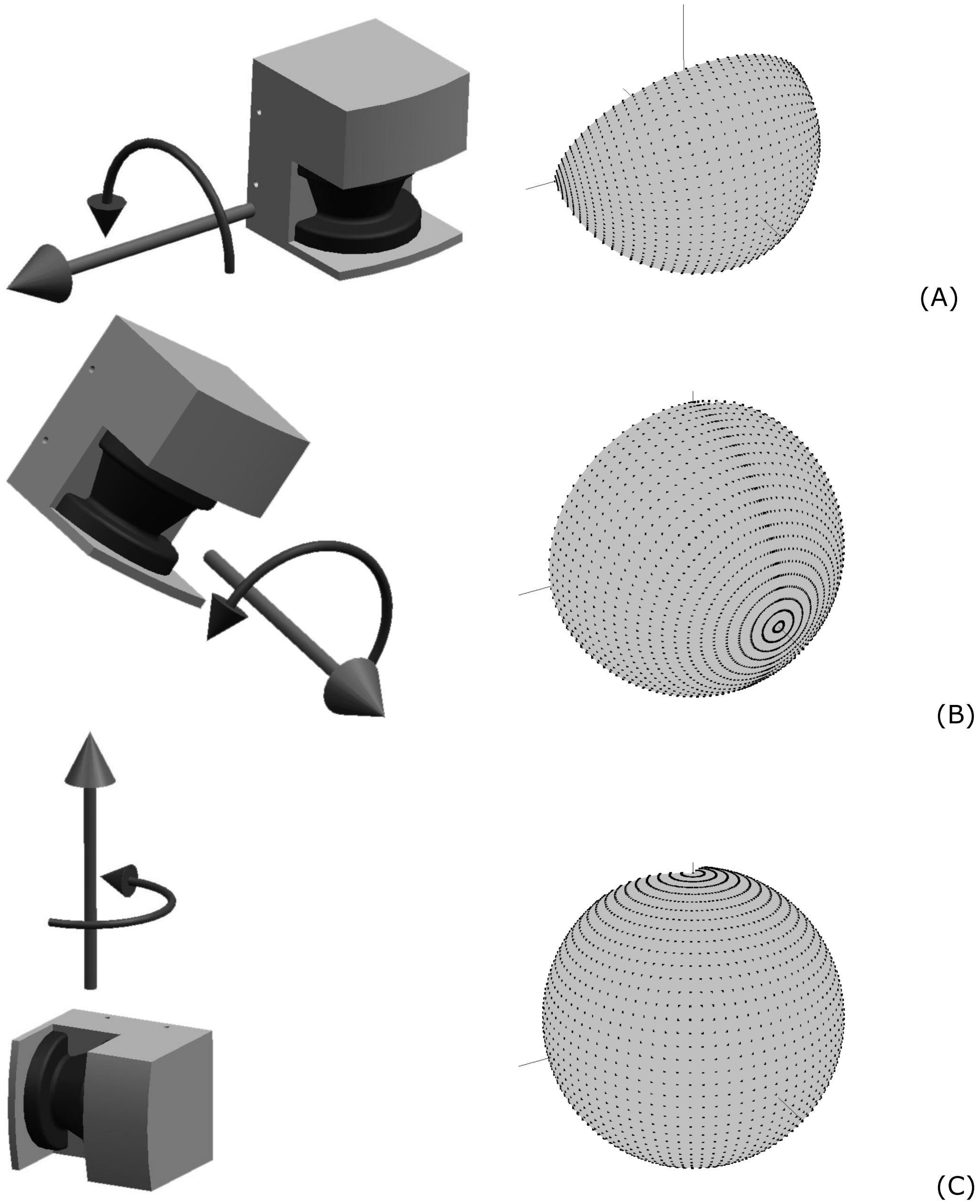


Figure 15: Scanning schemes (left) and measurements density distribution (right): (A) pitching scan, (B) rolling scan, (C) yawing scan (Wulf *et al.,* 2003)

Guaranteed Response: An 3D laser scanner uses an 2D laser scanner to scan the environment. The 2D laser scanner complies with the guaranteed response. The 3D laser scanner is then also capable of scanning up to 5.54 m. It fulfils the requirements for the guaranteed response.

Guaranteed Throughput: Scanning the environment with the apex angle of 180° x 180° will take 1.6 seconds (Wulf *et al.,* 2003). The throughput ratio becomes

$$\rho_{throughput} = \frac{v_{vehicle} \cdot \Delta t_{measurement}}{Y_F} = \frac{2.5 \cdot 1.6}{5.54} = 0.722$$

The 3D laser scanner complies with the guaranteed throughput.
Guaranteed Detection: The spatial resolution of the 2D laser scanner is also used in this calculation, because this resolution is used in this scanner as well. The acuity ratios are exactly the same. For the Boomer 3045 the acuity ratio will be

$$\rho_{acuity} = \frac{S_r}{L} = \frac{0.008}{1.87} = 0.004$$

For the Fendt 207V the acuity ratio becomes

$$\rho_{acuity} = \frac{S_r}{L} = \frac{0.008}{2.16} = 0.004$$

Guaranteed Localisation: The guaranteed localisation is the same as the 2D laser scanner and can be seen in 4.2.1.

4.3 Radar

A radar systems uses electromagnetic waves to determine the distance between the sender/receiver and the object. Electromagnetic waves are send away and will be reflected by the object back to the receiver. From this 'echo' several characteristics of the object can be derived like distance, height, speed and aiming. That is the reason that this type of environment scanning is used in the military. It is a fast scanning principle that gives measurements accurate enough. There are some drawbacks of the radar. Just a small amount of the energy that is transmitted into the environment is returning to the radar installation. The preferences is to have a strong transmitter, a sensitive receiver and a stable frequency. Next to that every object that reflects the electromagnetic wave will be seen, so filtering of the signal is important. The last drawback is the receiving of earlier send waves. When a wave travels further away that assumed the signal will be reflected later. The wave that is send after the initial wave will be seen as the initial wave and the distance calculation will be false. The solution to the last drawback is frequency modulation in which the frequency of transmitting is varied in time.

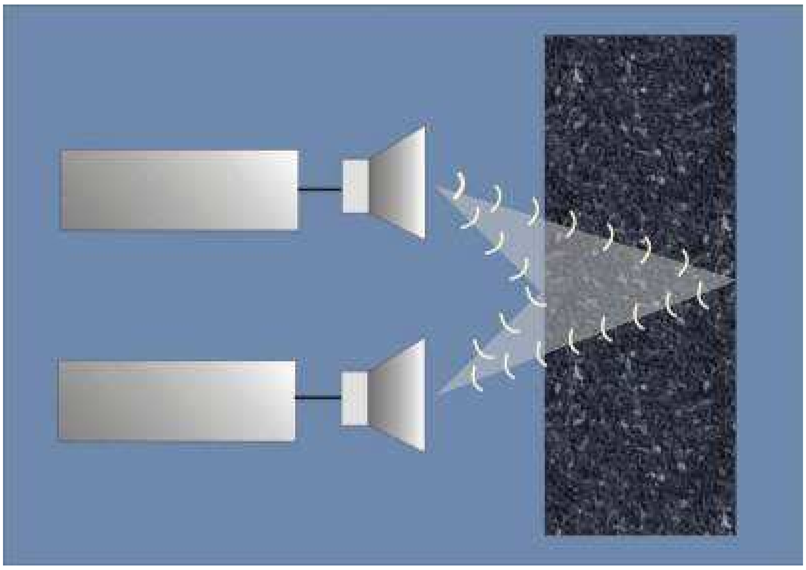


Figure 16: Radar installation (http://www.fhwa.dot.gov/engineering/geotech/hazards/mine/workshops/ktwkshp/ky0314.cfm#fig1)

In the article of Urmson *et al,* (2006) the radar for long-range detection of obstacles was mentioned. This radar system was used to track long range obstacles. This radar system is not applicable for this safety system. The radar sees the whole time objects in the long range, because the fields where the vehicle is operating are small. In the automotive industry the short range radar is used to detect objects in the direct environment of the vehicle. This radar system can also determine if an object will collide with the vehicle. (Bloecher *et al.,* 2009). The specification of these systems and specifically the radar itself is put under the non-disclosure agreement.
Guaranteed Response: The radar system in the automotive industry is capable to detect objects with substantial higher speeds than the spraying vehicle drives. The short range radar can see objects in the range of zero till 20 m (Wolfgang Lehbrink, 2008). The radar complies to the guaranteed response.
Guaranteed Throughput: The frequency of the signal is between 76.0 and 77.0 GHz (Bloecher *et al.,* 2009). This is the spectrum the European Conference of Postal and Telecommunications Administrations (CEPT) has determined for these systems from 1 July 2013. Before this date the spectrum of 24 GHz can be used. For the throughput the scan speed is of interest. The scan speed of this system could not be provided by the manufacture due to the NDA. The assumption is made that this value must be lower than 1 second. If this value is higher the system that is used in the automotive industry cannot guarantee that the objects are seen. The throughput ratio becomes

$$\rho_{throughput} = \frac{v_{vehicle} \cdot \Delta t_{measurement}}{Y_F} = \frac{2.5 \cdot 1}{5.54} = 0.451$$

The radar system complies with the guaranteed throughput.
Guaranteed Detection: The spatial resolution of the radars pixel footprint is not known and not given in the literature of the radar. The acuity ratio cannot be determined.
Guaranteed Localisation: The systematic error of the radar system could not be found. The error is hard to predict, because the radar system is depending on much variables. In one situation the radar could be high accurately while in another situation the object is not detected at all.

4.4 Ultrasonic sensors

Ultrasonic sensors use the same principle as the radar system, but instead of electromagnetic waves the ultrasonic sensors transmits sounds waves with a frequency that is higher than 18 kHz. These frequencies cannot be heard by the human ear. The

sound waves can travel through dust and other visual obscurants, just like radar. But the difference is the working range. Ultrasonic sensors have a working range of a few meters while radar can work properly for more than hundreds of meters. The beam that the ultrasonic sensor transmits is between 0.3 and 0.6 m wide, with the top detection range in the middle of the beam. On the ION autonomous vehicle that participated in the DARPA Challenge several ultrasonic sensors were placed to provide side sensing for narrow passages and rear sensing for the vehicle while driving in reverse (Özgüner et al., 2007). For the calculations the MaxBotix XL-MaxSonar-WR1 is taken as an example.
Guaranteed Response: The chosen ultrasonic sensor has a detection range between 0 m up to 7.65 m (MaxBotix, 2012). The scanning range is more than the required 5.54 m.
Guaranteed Throughput: Readings of the sensor can occur up to every 100ms, this means a frequency of 10 Hz (MaxBotix, 2012). The throughput ratio becomes

$$\rho_{throughput} = \frac{v_{vehicle} \cdot \Delta t_{measurement}}{Y_F} = \frac{2.5 \cdot 0.1}{5.54} = 0.045$$

The throughput ratio is sufficient small.
Guaranteed Detection: The output voltage of the sensor is given for certain distances and sizes of objects. At a distance of 7.04 m an obstacle of 1m by 2 m is detected by the ultrasonic sensor(MaxBotic, 2012). For the calculations the pixel footprint is set to 1 m. For the Boomer 3045 the acuity ratio will be

$$\rho_{acuity} = \frac{S_r}{L} = \frac{1.0}{1.87} = 0.53$$

For the Fendt 207V the acuity ratio becomes

$$\rho_{acuity} = \frac{S_r}{L} = \frac{1.0}{2.16} = 0.46$$

The acuity ratio with the Boomer is not under the threshold of one-half, the Fendt is above one-half.
Guaranteed Localisation: The systematic error of the radar system could not be found in the literature.

4.5 Camera Vision

A very handy tool in collecting information about the environment is a camera. With a camera images are made which can be processed into valuable data. An image is an 2D representation of the 3D environment. There are different sets of camera's that can be used to do this job.

4.5.1 Camera

In Figure 17 the main principle of every camera is explained graphically. Light that is reflected on an object comes in the lens that will converge the light beams. The aperture controls the amount of light that is pointed on the sensor, the shutter controls the time that the light beams are pointed. As a sensor a CCD or a CMOS is used to translate the information of the light beam to an electrical signal.

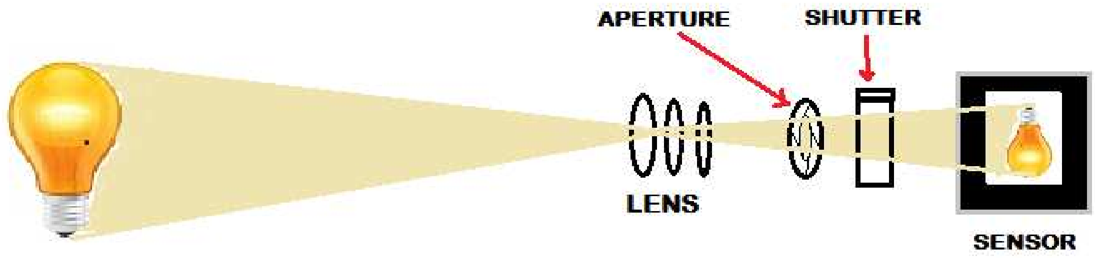


Figure 17: Principle of a camera (http://idigitalphotography.blogspot.com/2011/09/how-digital-camera-works-as-explained.html)

To see three dimensional it is necessary to have at least two different points of view. This can be accomplished by stereo vision. This consist of multiple cameras with a different field of view. This means that the images taken of the different cameras of the overlapping area can be compared to get information of the environment. The system is then capable to see three dimensional and can detect obstacles. Camera vision can also be done with infrared cameras who form images with infrared radiation (wavelenght beyond 780 nm) instead of visible light (380 – 700 nm). An infrared camera has the ability to see better during the night conditions because it sees temperature differences. These differences can be used to detect objects better during the night due to the lack of visible light. Stereo vision with infrared cameras is possible.

4.5.2 Calculations

Guaranteed Response: The placing of the camera determines if the camera has the required lookahead distance. If the placing is done correctly, the camera will comply with the guaranteed response.
Guaranteed Throughput: Readings of the camera can occur with time steps of milliseconds. The camera system that was mounted on the autonomous vehicle Caroline made 14 frames per second; 14 Hz (Rauskolb *et al.,* 2009). This results in a time interval of measurements of 0.07 s and the throughput ratio becomes

$$\rho_{throughput} = \frac{v_{vehicle} \cdot \Delta t_{measurement}}{Y_F} = \frac{2.5 \cdot 0.07}{5.54} = 0.032$$

The camera complies with the guaranteed throughput.
Guaranteed Detection: For the calculation of the acuity ratio the spatial resolution of the camera pixel footprint must be known. This is very much depending on the characteristics of the camera. That is the reason why we do is the other way around. We will calculate the desired spatial resolution instead of checking if the sensor complies with the requirements. For the Boomer 3045 the spatial resolution will be

$$\rho_{acuity} = \frac{S_r}{L} < 0.5 \rightarrow S_r \leq 0.935m$$

For the Fendt 207V the spatial resolution becomes

$$\rho_{acuity} = \frac{S_r}{L} < 0.5 \rightarrow S_r \leq 1.08m$$

An pixel height of 0.935 m and 1.08 m at a distance of 5.54 m can be accomplished by various cameras.
Guaranteed Localisation: No statements will be done on the guaranteed localisation.

4.6 TOF Camera

The Time-of-Flight camera calculate the distance to objects by measuring the phase shift φ_0 of the reflected light signal to the phase of the light signal of their light source for every pixel of the camera (Klose *et al.,* 2009). The camera uses amplitude modulated light and obtains the distance data by measuring the phase shift of the transmitted light. In Figure 18 the principle of the camera is illustrated.

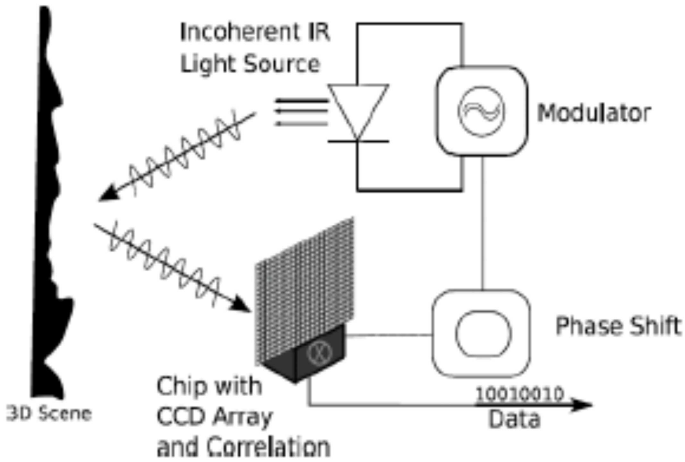


Figure 18: Principle of TOF camera (Kolb *et al.,* 2008)

To asses if the TOF camera can be used for the safety system I chose the PMD CamCube 3.0 camera for the calculations.
Guaranteed Response: The CamCube 3.0 has a measurement range between 0.3m and 7.0 m (PMD Technologies, 2012). This range is sufficient for the guaranteed response.
Guaranteed Throughput: The CamCube 3.0 makes 40 till 80 frames per second; 40 up till 80 Hz. The smallest ratio is 40 fps, so on this frame rate I will base my calculations. This results in a time interval of measurements of 0.03 s and the throughput ratio becomes

$$\rho_{throughput} = \frac{v_{vehicle} \cdot \Delta t_{measurement}}{Y_F} = \frac{2.5 \cdot 0.03}{5.54} = 0.011$$

This throughput ratio is small enough to comply with the guaranteed throughput.
Guaranteed Detection: At the maximum distance in the measurement range the spatial resolution of the pixel height will be 0.0128 m. For the Boomer 3045 the acuity ratio will be

$$\rho_{acuity} = \frac{S_r}{L} = \frac{0.0128}{1.87} = 0.007$$

For the Fendt 207V the acuity ratio becomes

$$\rho_{acuity} = \frac{S_r}{L} = \frac{0.0128}{2.16} = 0.006$$

The acuity ratio is sufficiently small.
Guaranteed Localisation: No statements will be done on the guaranteed localisation.

4.7 Discussion

A laser scanner makes accurate measurements of the environment. But the environment can deceive the scanner. The laser scanner cannot penetrate dust and will give false measurements in dusty environments (Urmson *et al.,* 2006). The environment of the spraying vehicle can become dusty and this has to be taken into account with the implementation of the scanner. When we look to the 3D laser scanner the scanning type is of influence for the detection of objects. How big this influence is, is not known. Testing the 3D laser scanner will make this more clear. It must be observed that the rolling scan has the most scanning dots in front of the laser scanner. This is not immediately the most appropriate scanning type, because the scanner also must look for obstacles in the front of the spraying boom. With the rolling scan the number of measurement dots at the end of the spraying beam can be so low that no objects can be detected.

Radar sensing of the environment has several advantages. It provides long range measurements and is not normally affected by dust, rain, smoke, or darkness. (Urmson *et al.,* 2006). Still the spatial resolution of the radars pixel footprint is not known and must be obtained by testing the radar in practice with different obstacles. Then a conclusion can be made about the guaranteed detection. The radar system that is used in the automotive industry is today commonly implemented in the high class cars. This system could be adjusted to perform in the environment of the spraying vehicle.

Ultrasonic sensors are very suitable to detect objects in the short range, smaller than 10 meters. The disadvantage is that they are sensitive for noise in the environment. The accuracy is greatly depending on this noise in the working environment. The ultrasonic sensor have a build-in noise rejection. This sensor is designed to operate in the presence of noise but will perform the best if the noise strengths are low and signal strengths are high. Noise from regularly occurring periodic noise sources such as fans and engines will not falsely be detected as an object and will be filtered out. The manufacturer advices to test the sensor in their application to verify the usability of the sensor. The acuity ratio that is calculated with the Boomer is apparently not sufficient. This is arbitrary, because the calculations is done with the results of an obstacle detection with a distance of 7.04 m. In the case of the spraying vehicle this range is 5.54 m, so quit smaller. The ultrasonic sensor must detect an object with a height of 0.935 m to have an sufficient acuity ratio. It is most likely that the sensor is capable to do this. Kelly *et al.* (1998) stated that the acuity ratio must be under one-half. This value is different for every vehicle, because it determines if the vehicle can cope with the objects.

Image acquisition by camera vision is a way to get much data on the environment. The success of the vision system to detect objects depends on the accuracy of the camera itself like the number of pixels and the spatial resolution. Also the quality of the images is depending on the illumination during the images acquisition. But the accuracy is even more depending on the data acquisition of the images. The software behind the camera determines if objects are detected or not. The system must be designed in such way that during different circumstances in the field (illumination, weather type, dust) objects will be detected by the system.

The TOF camera of PMD Technologies complies with all the requirements that are set for the safety system. However, the safety range can become a problem. At the maximum range the pixel height is 0.0128 m. The height and the width of the pixel is the same in this case, because of the same field of view (40° by 40°) and the same pixel range (200 by 200). This results in a field of view width of 2.55 m. The spraying width in the strawberry field is 4.5 m, so this camera is not capable to detect the obstacles in front of the sprayer boom.

It is clear that all sensors have their advantages and disadvantages. One single sensor type is not reliable enough to detect objects due to their limitations. The best way is to use multiple sensor types to overcome the capability gaps that exists in each sensor type. All vehicles that performed during the DARPA Challenges used multiple sensor types for obstacle detection. Using multiple sensors means that all data has to be combined in a proper way. The data fusion is very important in this context.

5 Existing safety system

When information of the environment is obtained by the sensors, this information is transformed into data about the environment. Based on this data the safety system must make a choice which action has to be executed. In the literature on safety systems that are used on autonomous vehicles the principle is pretty much the same for all systems. At first it must be stated that the system in which the vehicle is driving must be modelled. This is very important, because this model is used to judge the measuring information. Every safety system uses multiple sensor types that collect data from the environment. The sensors collect data about the same environment, so the data becomes redundant. This data is processed by the system into information and is judged in a specific way based on the model of the system. The judgement results in a classification of the different measurements. The system will then make the choice which action must be performed by the vehicle. This will be done by the decision algorithm that is specially designed for every vehicle (Labayrade *et al.,* 2007), (Urmsen *et al.,* 2006), (Rauskolb *et al.,* 2009), (Özgüner *et al.,* 2007), (Cheng, 2011). Because the existing safety systems work with this principle the design of the safety system for the spraying vehicle is done with the same approach. In this section the data fusion and the high-level control of the safety system will be discussed.

5.1 Data Fusion

The definition of data fusion is 'the theory, techniques and tools which are used for combining sensor data, or data derived from sensory data, into a common representational format' (Mitchell, 2007). The quality of the information output obtained from the system, known as synergy, can be improved. Data fusion of multiple sensors may improve the performance of the system in four different ways (Mitchell, 2007):

- Representation; The information at the end of the data fusion process has abstract higher level than each input data set.
- Certainty; We expect that the certainty of the data after fusion is bigger than the raw data before fusion.
- Accuracy; The standard deviation before fusion is larger than the standard deviation after fusion. Also noise and or erroneous will be eliminated. The gain in accuracy and the gain in certainty is correlated.
- Completeness; New information to the current knowledge of the environment will improve the view of this environment. Redundant information result in the gain in accuracy and certainty.

There are different fusion types appointed by Boudjemaa *et al.* (2004). In case of the spraying vehicle we talk about *fusion across attributes* where sensors measure different quantities associated with the same experimental situation. The configuration of the different sensors must be competitive with each other. The reason for that is that the aim of the data fusion in the safety system is to increase the accuracy and certainty. This can only be reached if there is redundant information about the environment. In the literature many different data fusion models are presented and explained. There are also engineering guidelines given which assist the practitioner in information gathering and decision-making (Esteban *et al.,* 2005). In the following pages a short introduction will be given in the architectures of a fusion system. Also some fusion techniques will be named, but not fully elaborated.

5.1.1 Architectures

Mitchell (2007) distinguishes four different data fusion networks, namely the single fusion cell (Figure 19), the parallel network (Figure 20), the serial network (Figure 21) and the iterative network (Figure 22).

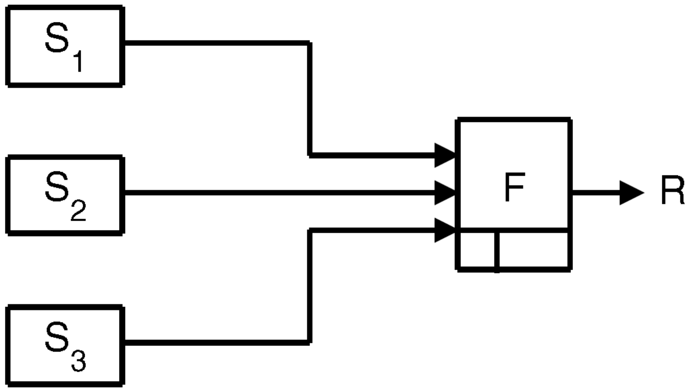


Figure 19: Single fusion cell network. (Mitchell, 2007)

In the single fusion network (Figure 19) cell the information of the different sensors is fully aligned by one fusion node. This node must have the capacity to process all information of the different sensors into the desired data.

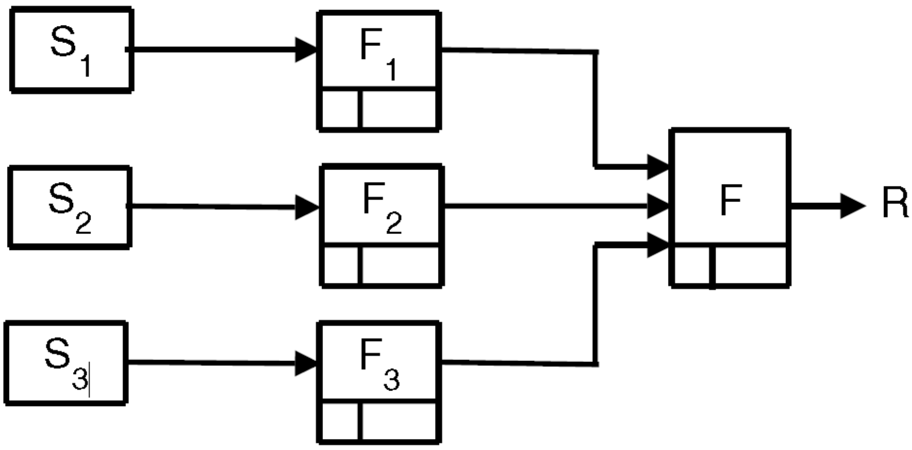


Figure 20: Parallel arrangement of three fusion cells Fm,m ∊ {1, 2, 3}. Each cell Fm acts as a virtual sensor which produces the input data Rm. The Rm,m ∊ {1, 2, 3}, are then fused together by F. (Mitchell, 2007)

Each fusion node F_m in the parallel network (Figure 20) processes the information provided by the sensors S_m. This result R_m is delivered to the overall fusion node F. The intermediate result of the fusion nodes is redundant and through the fusion process F the reliability and accuracy of the end result R is increased (Mitchell, 2007).
In the serial network (Figure 21) the fusion cells sends their results to the next fusion cell. These fusion cells gets information of sensors. Through this network the data that is send to the next fusion cell will become more heterogeneous and complementary.

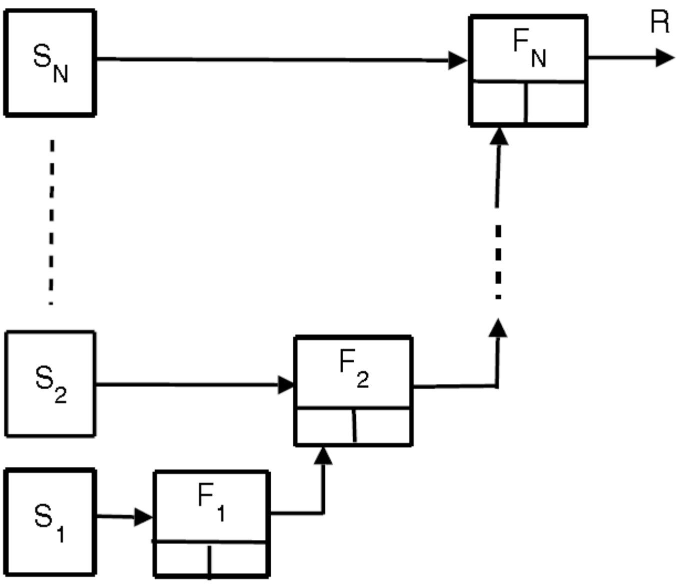


Figure 21: Serial network of multiple fusion cells. (Mitchell, 2007)

In the case of the single fusion cell network, the parallel network and the serial network that are shown here the measurements of the sensors can only be aligned. Filtering of the measurements by fusion techniques is not possible due to the lack of feedback to the fusion nodes. The fusion nodes that are displayed in these architectures can be replaced by the iterative node.

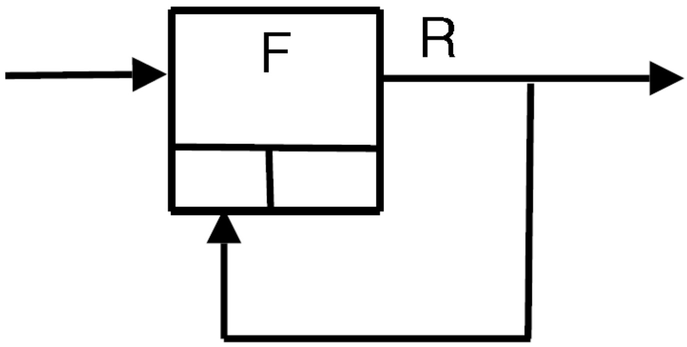


Figure 22: Single fusion cell operating in an iterative mode. The result R is re-introduced as auxiliary knowledge into F. (Mitchell, 2007)

In the autonomous vehicles that participated in the DARPA Challenges the data from the sensors was fused in different nodes who worked with the principle of the iterative network (Özgüner *et al.,* 2007) (Rauskolb *et al.,* 2009). Due to this architecture the fusion nodes are able to use strong fusion techniques, like the Extended Kalman filter or Particle filter. It is important to realize that the iterative fusion node can be placed into a different network like the parallel network. This gives a different architecture and give different results. An example of this network is the track-to-track fusion as can be seen in Figure 23. In this fusion process the sensors measurements are first corrected before they are fused together.

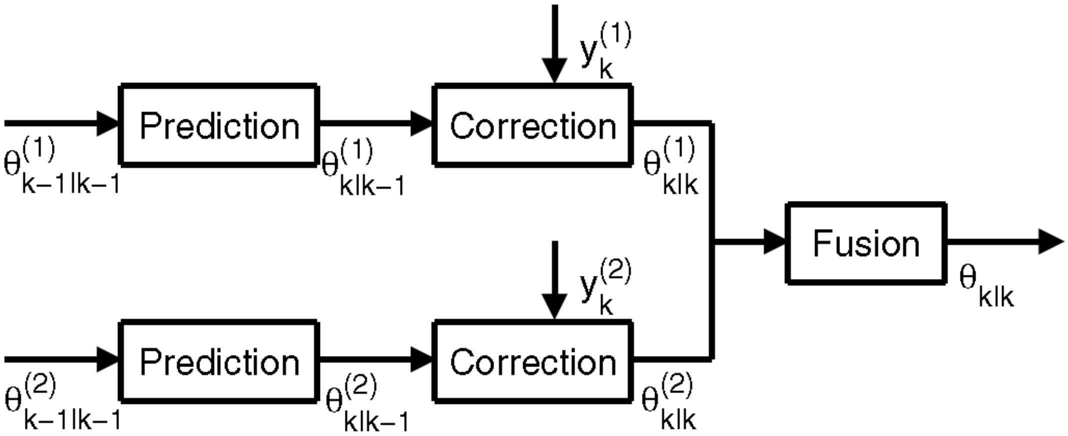


Figure 23: Track-to-Track fusion network. First there is a prediction of the environment based on the model and the previous measurements. This model is corrected by the environmental measurements (y_k) and at last both signals are fused together and give the output. The result that is re-introduced is not displayed in this figure. (Mitchell, 2007)

5.1.2 System fusion techniques

To combine all the data that is collected form the environment powerful fusion techniques must be used to avoid mistakes and errors of the system. Different techniques can be used to accomplish this. Most filter techniques are based on the Bayesian inference method, but contain different elements. Examples of these filters are the Kalman filters (Figure 24), Demster-Shafer filter (Rauskolb *et al.,* 2009) or Particle filters. In the autonomous vehicle Caroline different fusion techniques were used to fuse all data from the sensors. There are three conditions that have to be fulfilled for the fusion techniques:

- System model
- Measurement model
- Initial state

At first there must be a model available of the environment in which the safety system will operate. This model will describe in which state the system is operating. Secondly there has to be a measurement system that will supply the measurement model of measurements. At last the model needs to be initialized by an initial state. This can be seen as the beginning state of the spraying vehicle. When all these conditions are satisfied several fusion techniques can be used. In the next section two main filters of interest for the safety system will be discussed, namely the Kalman filter and the Particle filter.

5.1.2.1 Kalman filter

Mitchell (2007) described six different Kalman filters. All have different characteristics and work in a different field. The original Kalman filter only works for linear Gaussian systems. The working principle is shown in Figure 24.

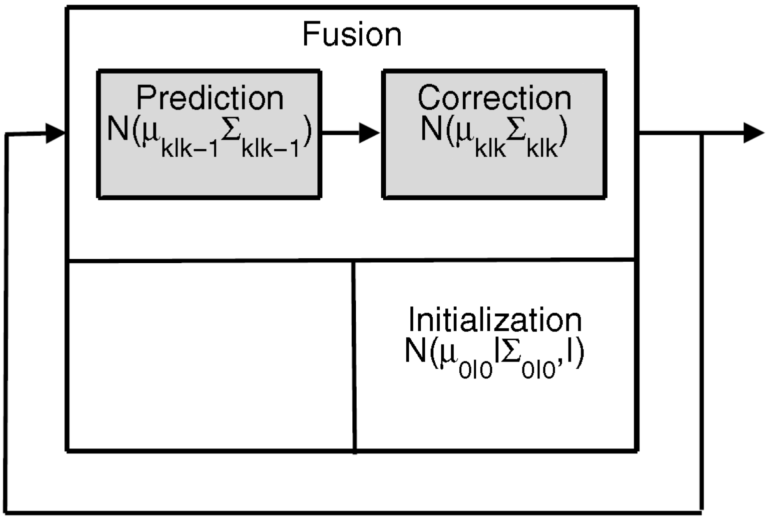


Figure 24: The main processing steps in the Kalman filter: (1) Initialization. We give initial parameter values ($\mu_{0|0}|I$) and $\Sigma_{0|0}|I$) and the noise covariances Q_k and R_k. This step is performed only once. (2) Prediction. We calculate a predicted pdf $p(\theta|y_{1:k}, I) = N(\mu_{k|k-1},\Sigma_{k|k-1})$ using the process model $\theta_k = F_k(\theta_{k-1}, v_{k-1})$ and the a posteriori calculated in the previous time step. (2) Correction. We calculate the *a posteriori* pdf $p(\theta_k|y_{1:k}, I) = N(\mu_{k|k},\Sigma_{k|k})$ by correcting the predicted pdf using the current measurement y_k (Mitchell, 2007)

In Figure 24 the basic steps of the Kalman filter are described. The system is initialized by the Initialization block. With this initialization the current state of the system is calculated with the system model (Prediction). In the upcoming loops the initialization parameters are replaced by the precious state parameters. The precious state is corrected by the measurements that are implemented in the Correction block (measurements y_k). The correction in the Kalman filter is based on the error between the systems parameters and the measurements. Because the normal Kalman filter is only applicable on linear Gaussian systems we have to use an extended version of the filter. The Extended Kalman filter is capable to linearize first-order non-Gaussian systems by using Taylor series expansions. When the system is more than a first-order system the linearisation will be done multiple times, because a second-order systems consist of two first-order systems.

5.1.2.2 Particle filter

Where the Kalman filter uses the error between the systems parameter and the measurements the particle filter does the correction in a different way. The measurement In Figure 25 the basic steps of the particle filter are displayed.

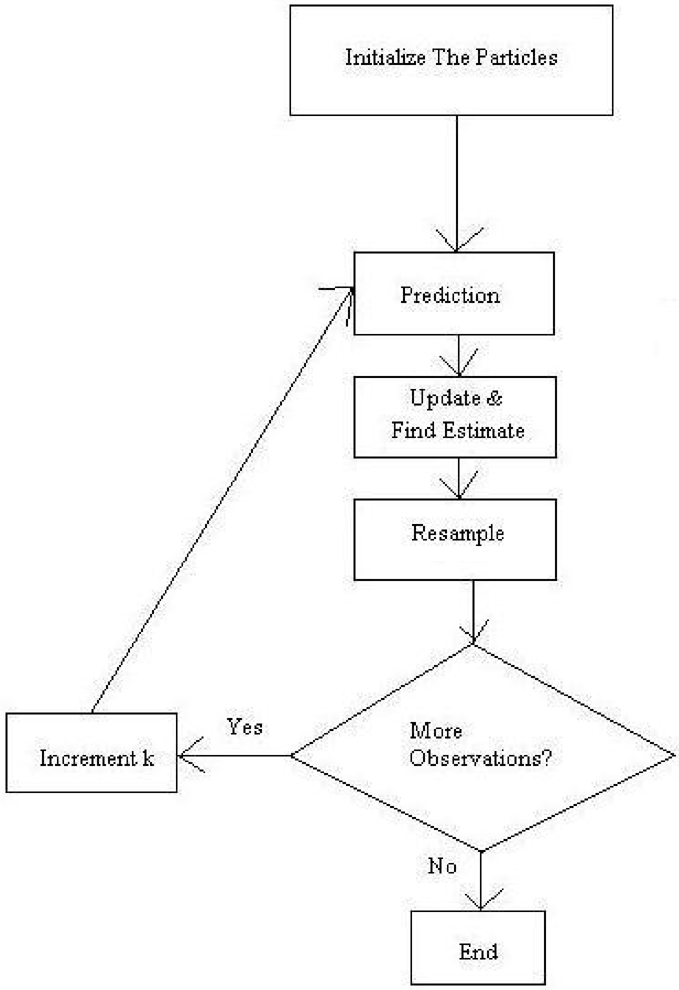


Figure 25: Basic steps in a particle filter algorithm (http://satnet.fgcu.edu/~zal/prognostics/ModuleX7.html)

In the first block 'Prediction' the current state of the system is calculated using the initial samples, called particles, or the observations of the previous state. The second block called 'Update & Find Estimate' the posteriori is estimated. Each particle is assigned a weight and these weights are normalized so that the sum of the weights of all particle is one. The third block is called 'Resample' and in this step a sample is taken from the discrete distribution and will replace the old particles in the model. The resampling is necessary to exclude the particles with a low weight. The particles with a low weight are likely to be false, with a high weight are likely to be true. More true particles will be selected in the resampling phase.

5.2 High-level control

Every autonomous vehicle is equipped with an overall control level. This high-level control is an autonomous driving system that is based on a classification of the environment (Özgüner *et al.,* 2007). From the environment the situation is recognized and understood and to this situation the appropriate behaviour of the autonomous vehicle is selected. The selected behaviour leads to a selection of controls, like speed, turning angle or distress call. The system is modelled as a finite-state machine. There is always a specific behaviour selected. The system must be taught in advance what different situations are. For every situation the appropriate behaviour must be programmed. The possible State Machine of the High-Level Control safety system for the spraying vehicle can be seen in Figure 26.

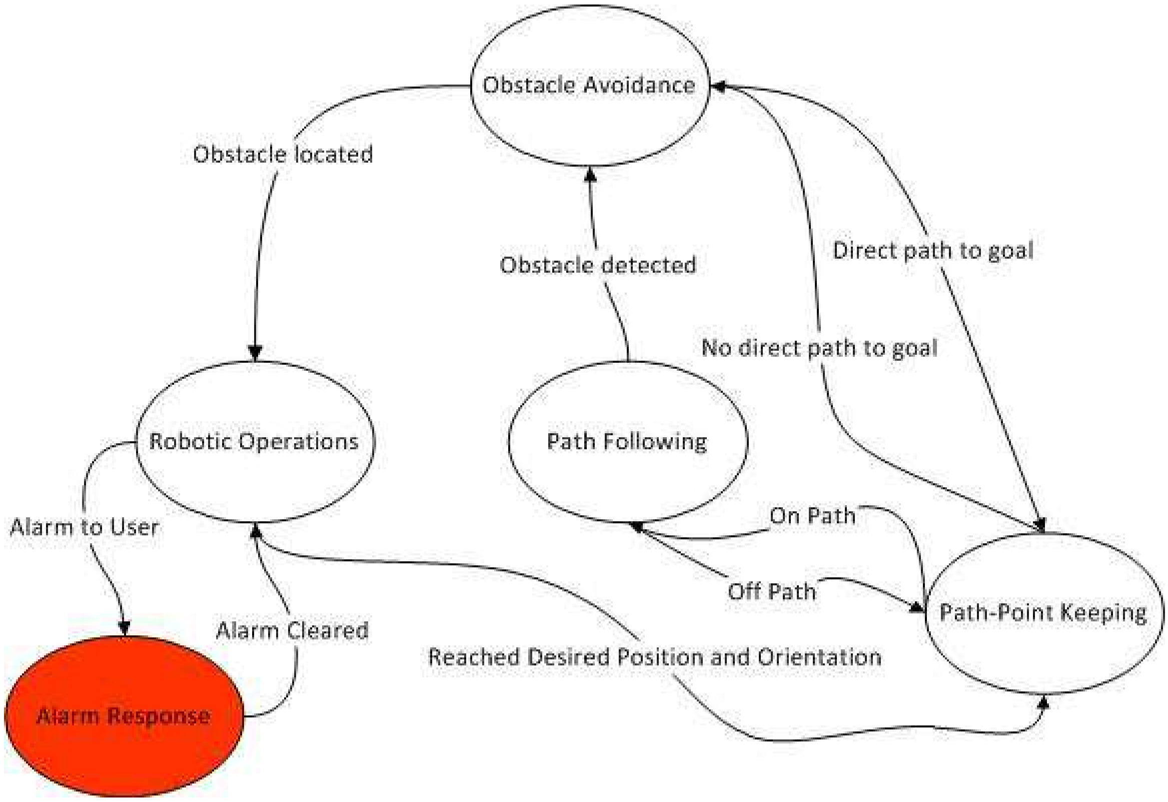


Figure 26: State Machine of the High-Level Control safety system for the spraying vehicle

In Figure 26 the five states of the control systems is shown. During the field work the spraying vehicle will be driving in the 'Path Following' state. In this state the fixed obstacles are used to program the possible route of the vehicle. When an obstacle is detected, the state 'Obstacle Avoidance' will be activated. When the obstacle is not in the path of the vehicle the state will go back to 'Path Following' through the state 'Path-Point Keeping', otherwise the state 'Robotic Operations' will be chosen. The system will decide if the robot will stop or will continue with driving. This state is mainly developed to extend the usability of the state machine, because the spraying vehicle will not make any avoiding manoeuvres. The action model presented in Figure 12 will be executed in this state. When the system decides that it cannot continue its path it will give an alarm response. A big advantage of the state machine is that is can easily combine the safety system with the navigation system. When both systems are controlled by the same state machine information can easily be exchanged.

5.3 Discussion

The serial network that is introduced in this section is not suited for the safety system, because it is mainly used to allow fast and efficient searches in databases. When a fusion nodes has sufficient confidence, for example, about the location of an object, it will skip the measurements of the other sensors. Information will not be redundant and the accuracy and certainty are not as high as in other architectures.
It is not feasible to give a precise layout or scheme for the implementation of any kind of sensor fusion application. The design of the fusion algorithms is a lengthy task where multiple fusion techniques can be combined (Navarro, 2008). This is the reason that the fusion design and implementation is not further described in this thesis. In this thesis only a proposing will be done for how the data fusion could be executed. It is possible to use a combination of different filters or elements of filters together. To properly design an overall fusion system every sensor must individually be investigated for their characteristics. Based on these characteristics the best fusion system and algorithm must be chosen.

6 Placing of sensors on spraying vehicle

The placement of the sensors on the spraying vehicle is of substantial importance, because it determines for a big part if the sensors can detect the obstacles. In this section a proposal will be given how to place the different sensors on the spraying vehicle to get the best detection results. This proposal will be done for every sensor individually. The placement of the sensors determines also which sensors could be combined to get the maximum detection possible. That is why a proposition will be made which sensors could be combined to get the best result. Radar is not mentioned in this proposition, because this sensor must be tested first if it can detect the obstacles in the way necessary for the safety system.
In Figure 9 the model to categorize the possible obstacles in the field is presented. In this model is shown that there are obstacles that are a hazard for the spraying vehicle and obstacle that are not a hazard. For the placement of the sensors the first group of obstacles is important, because this group has to be detected. The proposed placement of the sensors is presented In Figure 27.

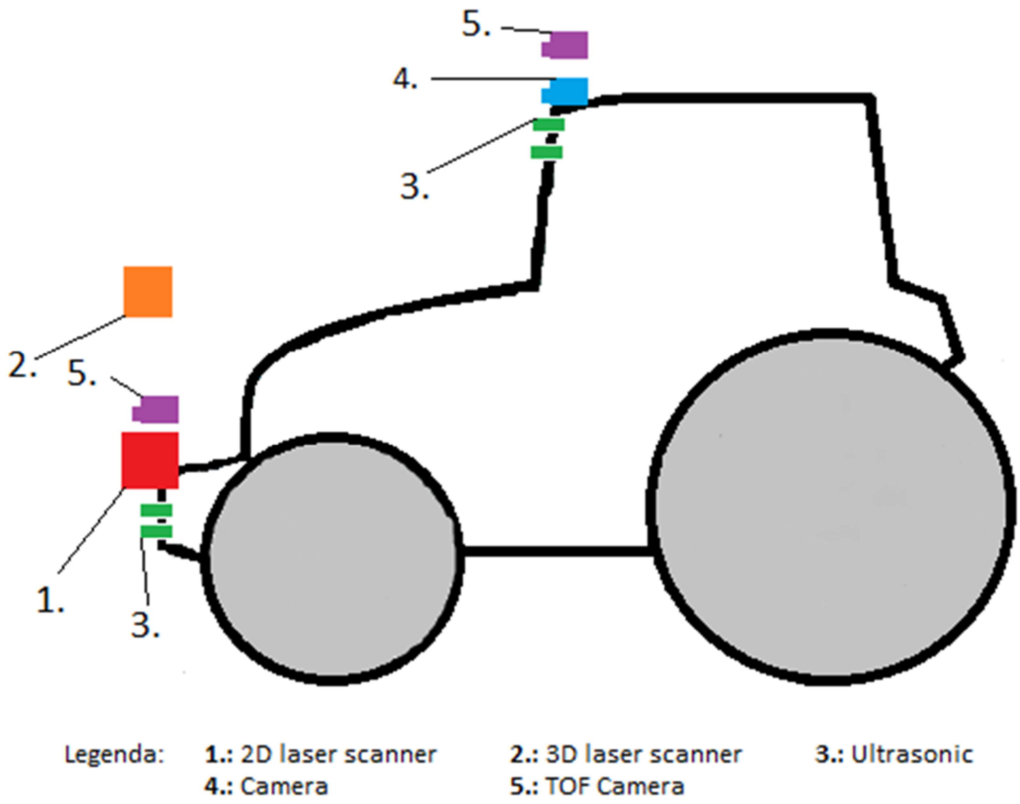


Figure 27: Schematic drawing placement of the sensors

6.1 2D Laser scanner

When the 2D laser scanner is mounted in front of the spraying vehicle and is scanning in the forward direction the laser scanner can detect most obstacles. In Figure 28 the laser beam is schematically drawn from the side of the vehicle.

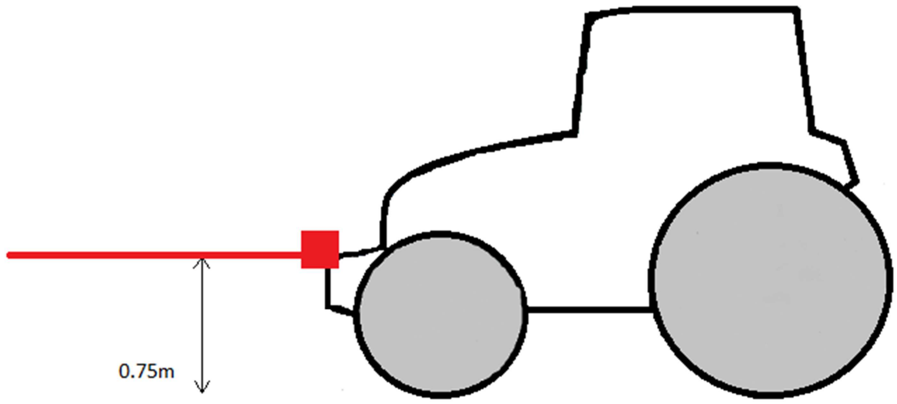


Figure 28: Schematic drawing of the laser beam (side view)

The obstacles that form a hazard for the vehicle are obstacles that can be detected on the height of approximate 0.75 m. When it is mounted on a height of between 0.75 m and 1.0 m the strawberry plants will not be seen as an obstacle. Of course this height may depend on the height of the strawberry plants. In the beginning of the season the scanner may be lowered to have a greater accuracy for the smaller obstacles. In the orchard the height of the laser scanner is the same as in the strawberry field. However, the measurements that detect the trees must be filtered from the measurements. At a height of 0.75 m the chance is bigger that the scanner will scan under the braches and will only detect the stems of the trees. This simplifies the filtering process. When the laser scanner is mounted at the same height as the spraying boom the obstacles that can hit the boom are detected. Making this height adjustable in the same way as the spraying boom is adjustable the detection of obstacles in front of the boom is covered. In Figure 29 the laser beam is schematically drawn from the top view. The fan-shaped scan pattern does not go further than the front wheels of the vehicle. These wheels will block the view of the laser scanner. The rest of the view is not blocked by the vehicle itself.

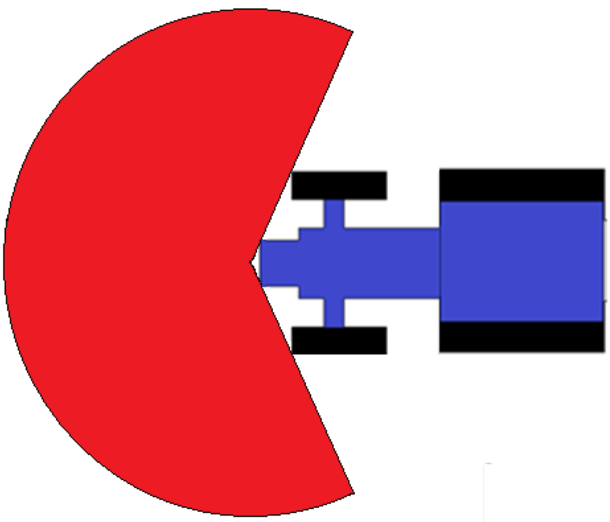


Figure 29: Schematic drawing of the laser beam (top view)

6.2 3D laser scanner

In Figure 30 can be seen that the 3D laser scanner is mounted at the half height of the vehicle. This means for the New Holland Boomer that the scanner is mounted at a height of 1.15 m and for the Fendt 207 at a height of 1.18 m. At this height the 3D laser scanner will have the same angle into the positive Z-direction as the angle to the negative Z-direction.

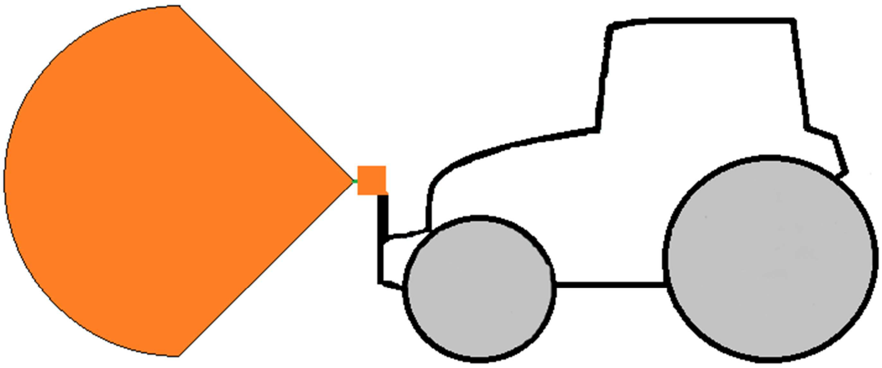


Figure 30: Schematic drawing of the laser beam of the 3D laser scanner (side view)

For the laser beam displayed in Figure 30 it does not matter which scanning pattern is used. All scanning patterns have the same measurement points in the range they scan. Between the scanning patterns there are differences. The best scanning pattern have to be assessed when this scanner is implemented. Only the filtering of the measurements has to be done properly, because the ground, sky and tree measurements must be filtered. The top view of the 3D laser scanner is the same as the 2D laser scanner and can be seen in Figure 29.

6.3 Ultrasonic sensors

The ultrasonic sensors are placed at two different positions. At first at the same position as the 2D laser scanner. The reasons for this place is the same as for the scanner. The second place for the ultrasonic sensors is the cabin of the vehicle (Figure 31). At this point the ultrasonic sensors are able to detect obstacles that are present at the height of the highest point of the vehicle, like hanging branches and machinery. These obstacles are more difficult to detect by sensors that are mounted at the front of the vehicle. In Figure 32 the top view of the ultrasonic is schematically drawn.

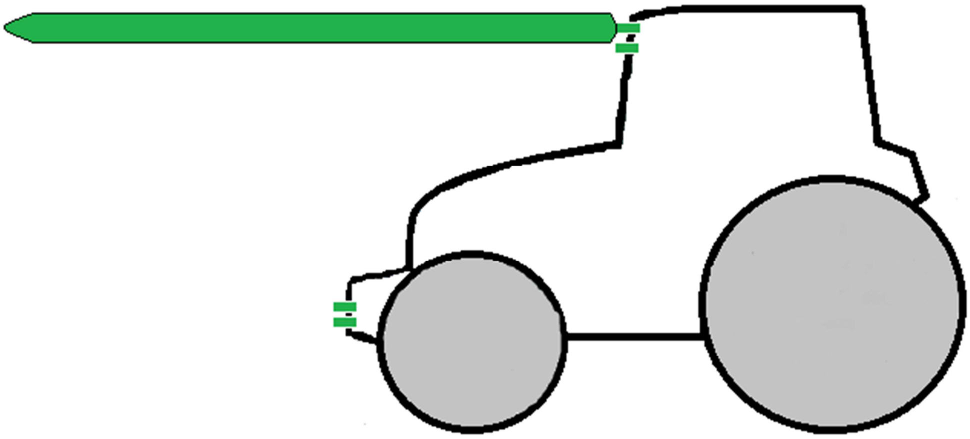


Figure 31: Sound beam of the ultrasonic sensor (side view)

On the KWH D-1000 V-3.2 orchard sprayer ultrasonic sensors to detect obstacles in front of the spraying boom are not necessary. This sprayer is not wider than the spraying vehicle itself. But on the spraying boom of the Sensispray-Horti strawberry sprayer some ultrasonic sensors can be placed to maximise the detection of obstacles.

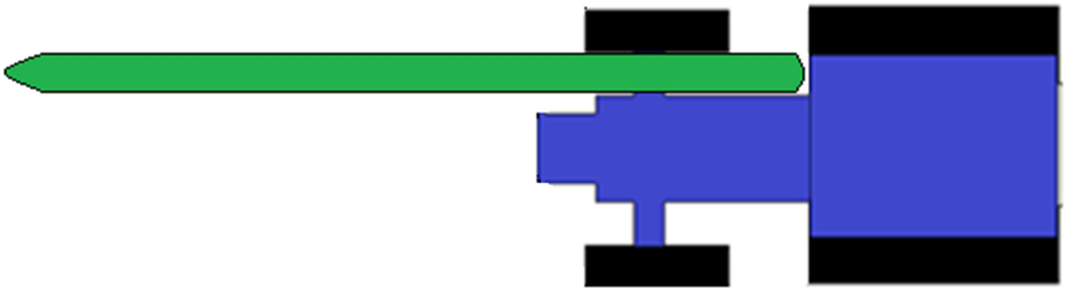


Figure 32: Sound beam of the ultrasonic sensor (top view)

6.4 Camera

The camera is mounted at the top of the cabin of the spraying vehicle. At this point the camera has the best view, due to the highest point advantages. At this point the camera must be able to detect obstacles that are placed at the beginning of the safety range, 5.54 in front of the vehicle. But also obstacles that are present at this height can be detected by the camera. The field of view of the camera can be seen in Figure 33.

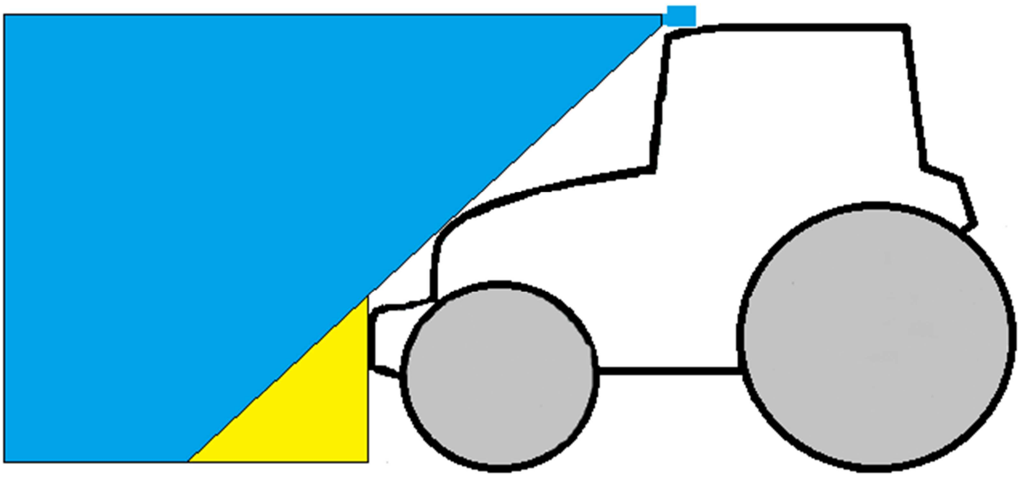


Figure 33: Field of view of the camera mounted at the cabin of the vehicle (side view)

The blue plane is the field that the camera can see. The yellow plane is the part that is blocked by the hood of the vehicle and therefor is not in the field of view of the camera. This is not a problem if the yellow plane is not larger than 5.54m in front of the vehicle. The field of view of the camera can be blocked by branches of the trees in the orchard. This means that the blue plane is interrupted and the camera cannot see at the ground surface. This has to be taking into account when the images are processed. The camera field of view seen from the top of the vehicle can be seen in Figure 34.

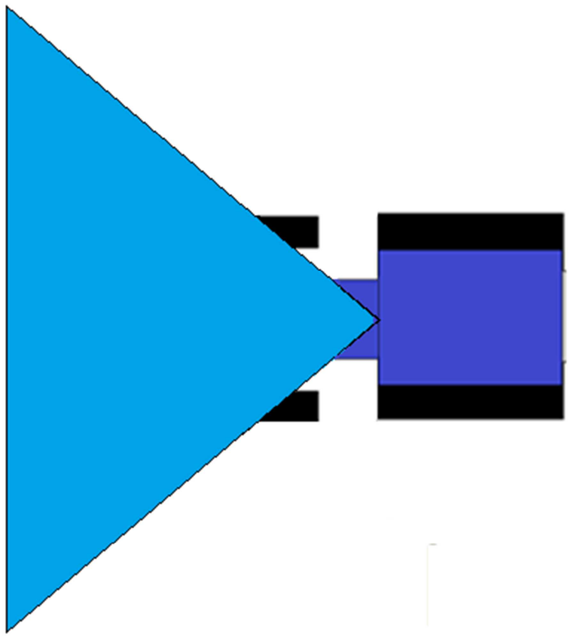


Figure 34: The camera field of view (top view)

6.5 TOF camera

The TOF camera can be mounted on two places, at the front of the vehicle and at the cabin. When the camera is mounted at the top of the cabin the TOF camera is at the maximum of its detection range. This range goes up to 7.0m (section 4.6). When the camera is mounted at the front of the vehicle the detection range is large enough. This will be the most appropriate place for the TOF camera with respect to this range. But the view of the camera can be blocked by branches at both heights, the same problem that can occur with the normal camera. The view of both cameras are the same. The side view can be seen in Figure 33, the top view in Figure 34. The view of the TOF camera is smaller than the normal camera, like mentioned before.

6.6 Combinations of sensors

Every sensor that is proposed has characteristics that make it more suitable for some types of obstacles and placements. Sensors must be combined to overcome the limitations of each sensor and to get a maximum detection rate. The next session discusses different proposed combinations of sensors to accomplish this.

6.6.1 Combination 1

The first proposed combination of sensors is the combination that is proposed by Labayrade *et al.* (2007):

- 2D laser scanner
- Vision camera

The side view of these two sensors can be seen in Figure 35.

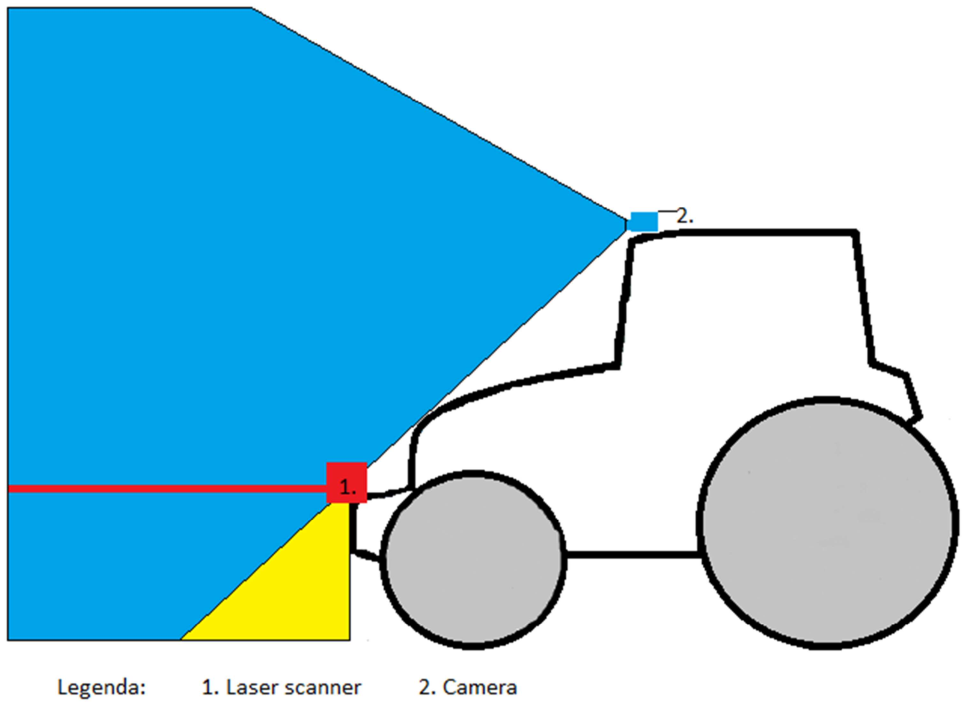


Figure 35: Schematic drawing of combination of sensors 1 (side view)

In this combination the limitations of the laser scanner are compensated by the vision camera. The laser scanner cannot detect the obstacles that are placed higher or lower than the mounting height of the laser scanner. Also the height of the obstacle cannot be estimated. The vision camera can detect these obstacles and can give estimations about the size of the obstacles. For the range of obstacles that form a hazard for the spraying vehicle both the laser scanner and the vision camera will detect these obstacles. For the spraying vehicle in the orchard the camera must see higher than the cabin of the Fendt 207, because the spraying boom is higher than the Fendt 207. When the view of the camera is blocked by branches or other objects the laser scanner sees this range. The yellow space is not covered by this combination of sensors. The laser scanner has a wide field of view, so it is able to detect obstacles in front of the boom. The laser scanner must hang at the same height as the spray boom. This means that the laser scanner must be adjustable in height. Obstacles that have the potential to hit the boom are then detected. No extra sensors on the boom are necessary.

6.6.2 Combination 2

The second combination of sensors is:

- 3D laser scanner
- Vision camera
- Ultrasonic sensors

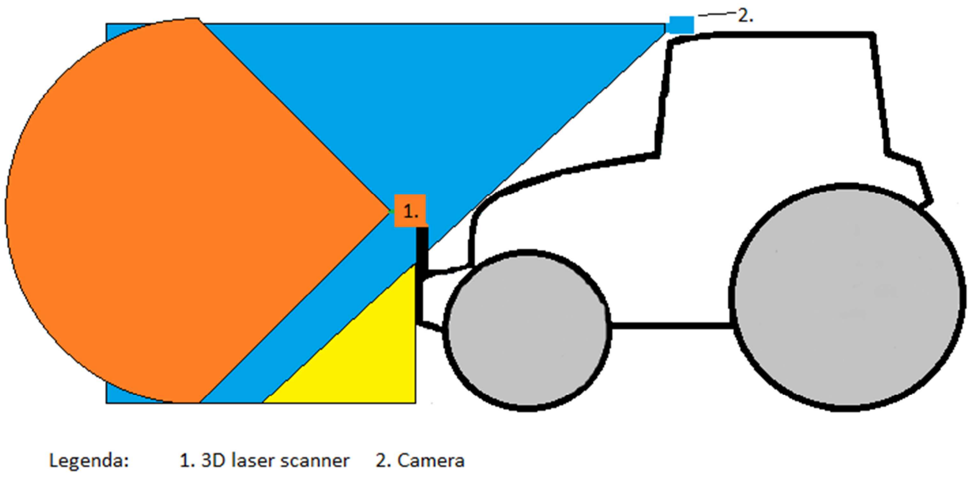


Figure 36: Schematic drawing of combination of sensors 2 (side view)

The side view of this combination of sensors can be seen in Figure 36. The 3D laser scanner is very capable in estimating the shape of the obstacles that are detected. The main advantage with respect to the 2D laser scanner is that the 3D laser scanner is able to estimate the height of the object. Together with the camera obstacles can be detected. Redundant measurements about the environment will be made. Combining these two sensors results in a cleaner 3D picture of static data points (Ortega *et al.*, 2011). The ultrasonic sensors are not drawn in Figure 36. It can be seen in Figure 36 that the laser scanner blocks the view of the camera partly. This view is blocked in line with the hood of the vehicle. The expectation is that this is just a small part of the view of the camera. This area is still covered by the 3D laser scanner.

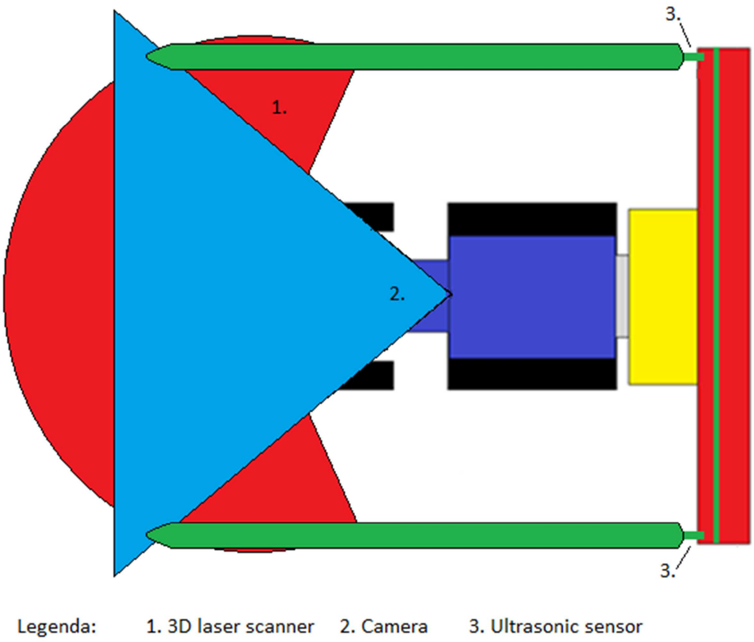


Figure 37: Schematic drawing of combination of sensors 2 (top view)

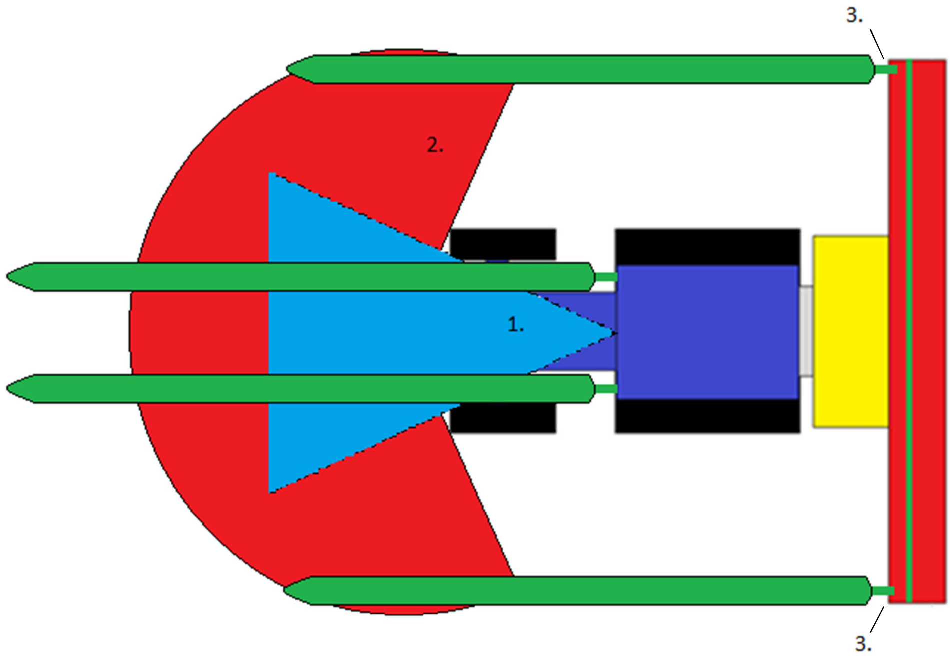
The 3D laser scanner is capable to detect obstacles in front of the spraying boom. The redundant data about this region must come from multiple ultrasonic sensors mounted on the spraying boom, if necessary. This depends on the scanning pattern that is used for the 3D laser scanner and the view of the camera. In this combination the pitching scan is the most appropriate, because this scan will have the most scanning points at the outer region of the scanning range. The camera will cover the area in front of the scanner. When the 3D laser scanner still has too few measuring points in front of the spraying boom or the view of the camera is blocked by objects the ultrasonic sensors can be used to overcome this detection gap. This is shown in Figure 37. For the sprayer in the orchard the ultrasonic sensors on the spraying boom are not necessary. This boom has the same width dimension as the Fendt 207. Only the height of the boom is larger, so it can be necessary to place these sensors at the highest point.

6.6.3 Combination 3

The third combination that is proposed in this section is:

- TOF camera
- 2D laser scanner
- Ultrasonic sensors

This combination can be seen in Figure 38. Here the top view is displayed.



Legenda: 1. TOF Camera 2. 2D laser scanner 3. Ultrasonic sensor

Figure 38: Schematic drawing of combination of sensors 3 (top view)

The TOF camera will detect obstacles in front of the spraying vehicle. Together with the 2D laser scanner this region will have redundant data. Also the 2D laser scanner will detect obstacles in front of the spraying boom. High obstacles will be detected by the ultrasonic sensors that are mounted on the cabin of the vehicle. If necessary ultrasonic sensors can be placed on the spraying boom to make sure that enough data is extracted of that region. For the sprayer in the orchard the ultrasonic sensors on the spraying boom are not necessary, only in the height of the boom. This height is larger than the Fendt 207.

6.7 Discussion

In the proposal of the placement of the sensors the radar system is not mentioned. The expectation is that the sensors used in this proposal are better suited for the job at hand. Still the radar system can be used for the safety system, especially when obstacles must be detected in the long range.
The proposed position of the 2D laser scanner is at the front of the vehicle to detect the obstacles at the most convenient height and as early as possible. It is also possible to put a second laser scanner at the same position as the ultrasonic sensors. This laser scanner can also detect hanging branches or other obstacles at that height. The expectation is that these measurements are more accurate than the ultrasonic sensors, but also more expensive. Some ultrasonic sensors are mounted on the front of the vehicle, but the effectiveness of these sensors at this place must be investigated. Because of the

characteristics of the sensors measurement signal, it is possible that it will detect only the trees and branches. This can be tested in practice.

Mounting sensors on the spraying boom can give improvements on the detection of obstacles in front of the spraying boom, especially when the safety sensors that are mounted on the vehicle are not able to cover this area. Even when these sensors cover the area it is possible that the detection rate is too low. The possibility of mounting sensors on the spraying boom has to be exploited.

The statement that no extra sensors on the spray boom are necessary with sensor combination 1 is a bit arbitrary. This must be checked in reality to make sure that this is the case. Applying some ultrasonic sensors can prevent some problems. In the proposed combination 3 the TOF camera is used to detect obstacles in front of the spraying vehicle, together with the 2D laser scanner. The detection rate of all proposed combinations must be tested in practice to know if it is sufficient.

In this placement proposal no suggestion are made about sensors at the back of the spraying vehicle. The same principles as the placement at the front of the spraying vehicle must be applied.

7 Discussion

The spraying vehicle that sprays in the strawberry field differs from the spraying vehicles that sprays in the orchards. Still one model is used to categorize these obstacles. This raises the question if the model could be applied on both spraying vehicles. The possible obstacles that the spraying vehicles can encounter are practically the same. Collisions with the two spraying vehicles and possible obstacles will have the same collision damage. Therefor this model can be applied on both spraying vehicles to categorize the obstacles. Because an obstacles is already assessed as hazard or not a hazard for the spraying vehicle The different categories of damage value could further be generalized. A suggestion is to make one category 'High collision damage' and 'Low collision damage'. Obstacles that are categorized as 'High collision damage' should then be treated in the design of the safety system above the obstacles categorized as 'Low collision damage'. The model cannot be used directly for the safety system in this form. The safety system cannot determine from the data of the existing sensors what the damage value is in a collision. Therefore a translation between a measurable quantity and the damage value must be made to use this model in the safety system. Size could be such quantity.

No humans will be in the surrounding of the spraying vehicle for supervision. When humans are in the safety range of the vehicle the vehicle must interfere to protect the human and itself. Adjustments to the vehicle itself could be a solution to prevent collisions with obstacles. For example a safety bar could be mounted in front of the vehicle and in front of the spray boom. The expectation is that this is not sufficient enough. When an obstacle hits this bar the collision is already a fact and damage could occur. An appropriate safety system must be designed to prevent collisions.

The policy of 'Guaranteed Safety', stated in Kelly *et al.,* (1998), is used to set requirements for the safety system. This policy can be divided into four different guarantees:

- Guaranteed response: The safety system must responds fast enough to avoid obstacles when they are detected.
- Guaranteed throughput: The model of the surrounding of the vehicle must be updated in a rate that is commensurate with the speed of the vehicle.
- Guaranteed detection: The safety system must detect obstacles that can become a hazard.
- Guaranteed localization: The safety system must accurately determine the place of an obstacle to have the possibility to make appropriate decisions.

The requirements are usable for the safety system that is designed for the spraying vehicle. The translation between the obstacle categorisation model and the requirements of the safety system must be executed. When it is known what obstacles for a hazard for the spraying vehicle the values for the ratios can be determined more precisely than the general values that are used in this thesis. The sensors can than more effectively be judged if they are usable for a safety system or not. For both spraying vehicles the requirements are set the same, because the obstacles that the spraying vehicles will encounter are the same. The spraying vehicles are not the same, the dimensions differ. This is not a reason to change the requirements that are set for the safety system. This difference must be resolved by the placement of the sensors on the spraying vehicle.

In the assessment of the different proposed sensors it came forward that one sensor is not sufficient enough to comply to the policy 'Guaranteed Safety' of Kelly *et al.,* (1998). Every sensor has it limits with respect to their sensing capabilities. Weather conditions could be of influence, but also environmental conditions and the working principle of the sensor limits the sensing capabilities. Combining sensors that are complementary with respect to their working principle and resistance to the external influences can solve this problem.

The high-level control of the safety system works on autonomous vehicles with the same principle. When the majority of safety system on autonomous vehicles works with this principle it makes clear that the state machine for the high-level control is very usable tool for the control of the safety system. Only differences on detail level can be found. These differences are the result of the sensors that are used or the different application of the vehicles. The state machine that is developed in section 5.2 has the state Path-Point Keeping. This state is not very usable for the safety system, because no evasion manoeuvres will be made. No Path-Point Keeping is in the state machine because in the future this state is needed when the spraying vehicle must drive from one field to another. Then evasion manoeuvres can be necessary.

The proposed combinations of sensors do not differ in detection rate and range. This was the intention, because the combinations must comply to the same requirements. The differences between the two spraying vehicles with respect to the safety system is resolved by the different placement of the sensors. Choosing between the combinations is therefore not easy. The less sensors there have to be used, the less effort it takes to build the safety system. From the proposed sensors combination the combination with the smallest amount of sensors must be chosen. All combinations are made in such way that they could be applied on both spraying vehicles. Costs could also be a good point to make this decision. When costs are taking into account the whole price tag must be known. The purchase cost, but also the implementation costs. Less sensors means less implementation costs, not specifically less purchasing costs. However, in this research the costs of the sensors are not taken into account. This is not a decision rule. The three proposed combinations are not the only combinations possible. Other combinations can be possible. Maybe some illogical combinations will come forward when the sensors are tested in working conditions. When these combinations perform better than the proposed combinations in section 6.6 these combinations must be used. The proposed combinations are combinations that have proven themselves on autonomous vehicles (Labayrade *et al.,* 2007). Only by testing the combinations a hard conclusion can be made which combination is best suitable for the spraying vehicle.

8 Conclusion

The model to categorize the obstacles is usable for both the spraying vehicle in the strawberry field and the spraying vehicle in the orchard.

The general policy 'Guaranteed Safety' of Kelly *et al.* (1998) is usable for the safety system on the spraying vehicle. The different sensors must be assessed by these requirements.

Several sensors are suitable to detect obstacles in this safety range:
- 2D laser scanner
- 3D laser scanner
- Ultrasonic sensors
- Camera
- TOF Camera

All these sensor comply with the requirements 'Guaranteed Safety'.

One sensor is not sufficient enough. Multiple sensors for sensing in the surrounding of the vehicle are needed. The extended Kalman filter or the particle filter are the two main fusion techniques of interest for the data fusion in this safety system.

The state machine control of the autonomous vehicle is an usable and powerful tool that must be applied on the safety system.

The combination of the 2D laser scanner and the camera is the best choice for the safety system. The 2D laser scanner must be mounted on front of the spraying vehicle, the camera on the cabin. This combination is the easiest to implement and implementable on both spraying vehicles.

9 Recommendations

To use the model for the categorization of obstacles in the safety system the translation between a measurable quantity and the damage value must be made. For this the measurable quantity has be determined. Then the relation between this quantity and the damage value have to be made. Size could be a quantity that is usable. It is possible that the measured quantity has no direct relation with the damage value. Maybe an extra relation step is needed to make this translation.

Knowing how the different sensors perform in the real environment is very important. Testing the sensors en compare these test results with the proposed requirements will give certainty about their ability to comply with the requirements. When the sensor are tested the radar system can be judged if it is applicable in the safety system.
The sensors must be tested in working conditions. This means that the sensors must be mounted on the proposed places on the spraying vehicle. Different obstacles that are mentioned in the model must be placed in the safety range. The sensors must detect these obstacles properly. When the sensor individually can detect the obstacle in the safety range the proposed combination of 2D laser scanner and camera can be tested. Of course the fusion model must be ready at that point.

Because there exist many different data fusion techniques and algorithms this part must be investigated intensively. All measurements of the sensors will come together in this part of the system. For that reason the data fusion part in the safety system can make a success of the system or it will cause total failure. Good research about the appropriate fusion architecture and the fusion technique for the proposed combination of sensors will lower the change of failure of the system.

There are three combinations of sensors proposed in the last section. The first combination comes forward as the combination that is the easiest to implement. The costs of this combination is not taking into account. It is possible that another combination has lower costs than this combination. The costs of the implementation of the sensors must be examined.

Rauskolb *et al.* (2009) discussed the implementation of a so called Watchdog. This Watchdog monitors the entire system in its performance. When a part of the system does not reply to the Watchdog, the system will interfere. In principle you can see this as an extension of the safety system that is described in this thesis. In an autonomous vehicle it is very important to let the system perform in the appropriate way. Monitoring the entire system can be the job of the safety system. This option can be investigated to ensure the safety even better.

10 References

AGCO GmbH – Fendt – Marketing, 2012. "Fendt 200 Vario V/F/P". Brochure 2012, 200V/1.1-NL/03-09/4.0-E

Bloecher, H.L. Sailer, A. Rollmann, G. Dickmann, J. 2009. "79 GHz UWB automotive short range radar – Spectrum allocation and technology trends". Advanced Radio Science, Vol. 7, pp. 61-65

Boudjemaa, R. Forbes, A. B. 2004 "Parameter Estimation Methods for Data Fusion", National Physical Laboratory Report No. CMSC 38-04

CBS, 2011. Fruitteelt; oppervlakte fruitboomgaarden; soort fruit; statline.cbs.nl/StatWeb/publication/?VW=T&DM=SLNL&PA=70671NED&D1=a&D2=a&HD=090707-1512&HDR=G1&STB=T (10-04-2012)

Cheng, H. 2011. "Autonomous Intelligent Vehicles: Theory, Algorithms and Implementations", First Edition, London

Dickmanns, E.D. 2003. "Expectation-based, Mulit-focal, Saccadic (EMS) Vision for dynamic scene understanding", Mathematical Methods in Computer Vision, Vol. 133, pp. 19-35

Dietmayer, K. C. J. Sparbert, J. Streller, D. 2001. "Model based object classification and object tracking in traffic scenes", IEEE Intelligent Vehicle Symposium Tokyo, pp. 25–30

Esteban, J. Starr, A. Willetts, R. Hannah, P. Bryanston-Cross, P. 2005. "A review of data fusion models and architectures: Towards engineering guidelines", Neural Computing & Applications, Vol. 14, Issue 4, pp 273-281

Kelly, A. Stentz, A. 1998. "Rough Terrain Autonomous Mobility—Part 1: A Theoretical Analysis of Requirements". Autonomous Robots 5, pp. 129–161

Klose, R., Penlington, J. Ruckelshausen, A. 2009. "Usability study of 3D Time-of-Flight cameras for automatic plant phenotyping", Bornimer Agrartechnische Berichte, Vol 69, pp. 93-105

Kolb, A. Barth, E. Koch, R. 2008. "ToF-Sensors: New Dimensions for Realism and Interactivity", 2008 IEEE Computer Society Conference on Computer Vision and Pattern Recognition Workshops, pp. 1518-1523

Labayrade, R. Gruyer, D. Royere, C. Perrollaz, M. Aubert, D. 2007. "Obstacle Detection Based on Fusion Between Stereovision and 2D Laser Scanner", Mobile Robots: Perception & Navigation, pp. 91-110

Martínez, J.L. Pozo-Ruz, A. Pedraza, S. Fernandez, R. 1998. "Object following and obstacle avoidance using a laser scanner in outdoor mobile robot auriga-α", 1998 IEEE/RSJ International Conference on Intelligent Robots and Systems - Proceedings, pp. 204-209

MaxBotix Inc. 2012. "Datasheet XL-MaxSonar WR1", PD10024e

Mendes, A. Conde Bento, L. Nunes, U. 2004. "Multi-target Detection and Tracking with a Laserscanner", Proceedings of the 2004 IEEE Intelligent Vehicles Symposium, pp. 796-801

Mitchell, H.B. 2007. “Multi-sensor Data Fusion: An Introduction”, First Edition, Berlin

Navarro, A. 2008. “Multisensor Data Fusion” Research Assignment, Master Programme MKE, TU Delft

New Holland Brand Communications. 2012. “New Holland Boomer”, Brochure 2012, 80017/NLO

New Holland Brand Communications. 2012. “New Holland T4 Powerstar”, Brochure 2012, 110001/NLO

J. Michielsen, J. Van De Zande, J. Nieuwenhuizen, A.T. Kempenaar, C. Stallinga, H. Van Velde, P. 2012. “Spuitvloeistofverdeling van de Sensispray-Horti in aardbeien 2011”. PRI Wageningen UR

Ortega, A.A. Andrade-Cetto, J. 2011. “Segmentation of dynamic objects from laser data”, Proceedings 5th European Conference on Mobile Robots, pp. 115-121

Özgüner, Ü. Stiller, C. Redmill, K. 2007 “Systems for Safety and Autonomous Behavior in Cars: The DARPA Grand Challenge Experience”, Proceedings of the IEEE, Vol. 95, Iss. 2, pp. 397-412

PMD Technologies.” 2012 PDM [vision] CamCube 3.0, High resolution 3D video camera, Datasheet”, V. No. 20100601

Rauskolb, F.W. Berger, K. Lipski, C. Magnor, M. Cornelsen, K. Effertz, J. Form, T. Graefe, F. Ohl, S. Schumacher, W. Wille, J. Hecker, P. Nothdurft, T. Doering, M. Homeier, K. Morgenroth, J. Wolf, L. Basarke, C. Berger, C. Gülke, T. Klose, F. Rumpe, B. 2008. “Caroline: An Autonomously Driving Vehicle for Urban Environments”, Journal of Field Robotics, Vol. 25, Iss. 9, pp. 674-724

Reinhoudt, K. 1986. “De V-haag bij peren”. De Fruitteelt: weekblad van de Nederlandse Fruittelers Organisatie. Vol. 76, Iss. 4, pp. 98-99

Scheerlinck, E. 2008. “Plantsystemen bij Conférence”; BSc thesis, K.U. Leuven

SICK Sensor Intelligence. 2009 “LMS100/111/120/151 Laser measurement systems, Operating Insturctions”, 8012471/T763/2009-07-28

Sijbrandij, F. 2012. “Decision algorithms for an automatic autonomous orchard sprayer”. MSc thesis, Wageningen UR

SWOV. 2010. “SWOV-Factsheet, Verkeersveiligheidsaspecten van landbouwverkeer”

Information Orchard system. www.fruitteeltonline.nl/ (10-04-2012)

Urmson, C. Ragusa, C Ray, D. Anhalt, J. Bartz, D. Galatali, T. Gutierrez, A. Johnston, J. Harbaugh, S. Yu Kato, H. Messner, W. Miller, N. Peterson, K. Smith, B. Snider, J. Spiker, S. Ziglar, J. Whittaker, W. Clark, M. Koon, P. Mosher, A. Struble, J. 2006. “A Robust Approach to High-Speed Navigation for Unrehearsed Desert Terrain”, Journal of Field Robotics, Vol. 23 Iss. 8 pp 467–508

Wolfgang Lehbrink, T.H. 2008. “Radar-Chips aus SiGe”, Radarsensoren auf Basis von SiGe-Transceivern. Automotive 03-04, pp. 14-18

Wulf, O. Wagner, B. 2003. “Fast 3D Scanning Methods for Laser Measurement Systems”, Proceedings of the International Conference on Control Systems and Computer Science, Vol. 1, pp. 312-317

Ye, C. Johann Borenstein, J. 2002. “Characterization of a 2-D Laser Scanner for Mobile Robot Obstacle Negotiation”, Proceedings of the 2002 IEEE International Conference on Robotics and Automation. pp. 2512-2518