Current Developments of High-Tech Robotic and Mechatronic Systems in Horticulture and Challenges for the Future

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Abstract

This paper reviews the current developments of high-tech robotic and mechatronic systems in horticulture and future perspectives. Driving forces for mechanization are identified. Dutch greenhouse crop production is used as an example. In greenhouse horticulture the production steps and control that needs to be done in the growing area of high value crops and flowers are still often done manually. Growers are investing a lot of labour in processes like crop sensing, crop maintenance and harvesting the products. To harvest these high value products, a lot of human intelligence is required, such as precise, effective and efficient eye-hand coordination in a complex environment, decisions concerning quality and ripeness and careful handling and buffering of variably shaped vulnerable products. Within the next years the first generation of machines will be introduced in greenhouse horticulture using principles of mechatronics and robotics, combining smart mechanical design with sensors and 'artificial intelligence' needed for these difficult tasks. Examples are the current commercial robot developments for cutting roses, harvesting strawberries and cucumber. But jumping from fully manual production to fully robotised production is a complex challenge and probably not always and not yet the way to go. As an intermediate step, also technology is needed to support current human labour for instance to harvest more precise, targeting on specific quality as a post-harvest feedback and to buffer the high value products carefully and automatically and it is even possible to support human labour by pointing out the ripe products that need to be harvested. Ambient intelligence is more and more becoming a part of the working environment. Here the idea is presented that new ICT developments in gaming can stimulate labour in greenhouse horticulture to do the work better and faster with a lot more fun when there is the challenge to reach new skills, features and levels supported in a gaming environment. Finally, progress in the field of greenhouse robotic and mechatronic systems does not only rely on innovations in the field of robot and mechatronic systems but also on necessary innovations in the field of growing systems and plant breeding to reduce variability and thus to simplify the task for men and machinery.

DRIVING FORCES FOR MECHANIZATION IN DUTCH HORTICULTURE

In Dutch horticulture the following driving forces for mechanization have been identified:

1. Increasing size of production facilities.
2. Specialisation of crop production and individualisation of plant treatment.
3. Increasing labour costs.
4. Increasing problems with the availability of skilled labour.
5. Health problems.
6. Product quality, food safety.
7. Growing competition on the national and international market.

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8. Chain integration.

Increasing Size of Production Facilities

In 1990, the greenhouse crop production area in the Netherlands amounted to 10000 ha, with more than 14000 companies. In 2007, the production area was still about 10000 ha, but the number of companies had declined to about 7000. So, the average size of a commercial greenhouse facility increased from 0.7 to 1.4 ha between 1990 and 2007. Extrapolation of this trend suggests that the average greenhouse size will be about 5 ha in 2030. This means that, if the total greenhouse area remains the same, the number of companies will drastically reduce to a relatively small number of large sized producers. This trend is already visible today. The number of small sized companies of less than 1 ha rapidly decreases. About 10% of the companies have a production area of 2.5 ha or more, covering 60% of the total production area. And companies with 30 ha of greenhouses are not a rarity anymore. Dutch greenhouses are highly productive. As an example it is possible to produce up to 100 kg of tomatoes per square meter every year. Productivity per square meter is important because more than 50% of the costs are energy costs and capital costs associated with investments in the greenhouse and its equipment.

Specialisation of Crop Production and Individualisation of Plant Treatment

There is a distinct trend of specialisation of crop production and individualisation of the treatment of crops. This seems contradictory to the previous trend of up-scaling of the production area per nursery but it is not. Companies shift from bulk production to the production of high quality produce or specialties. Growth and development of individual plants is monitored and action is taken to meet the requirements imposed by consumer groups. As a consequence greenhouse crop production becomes more and more labour intensive.

High Labour Costs

In Dutch horticultural crop production, labour is the largest cost factor with 31% of the total production costs for vegetables (Koren and Boon, 2005), 30% for cut flowers and 30% for potted plants in 2000 (Mentjox and Boon, 2006).

Problems with the Availability of Skilled Labour

In the Netherlands, a job in greenhouse crop production is not very prestigious and the wages are low, so growers have considerable problems acquiring skilled labourers. The expansion of the European Community with countries from Eastern Europe did alleviate this problem partly on the short term, but people are staying for a short period and problems with language and education will not be resolved in that way on the long term.

Health Problems

Compared with standard industrial practice, the working environment in greenhouses is not very comfortable. Both temperature and humidity are high and are getting more extreme due to developments in the direction of more closed greenhouses, high temperature loving cultivars, artificial lighting (also LED) and increased CO_2 levels.

Although the products are not heavy and the work can be done with automated guided vehicles, the repetition of tasks performed while the worker has an unfavourable posture, results in musculoskeletal disorders amongst which back injuries and Repetitive Strain Injury (RSI) are the most common.

Product Quality, Food Safety

Today, it is the consumers wish to eat food that meets high quality and safety standards and growers need to take measures accordingly during crop production.

Growing Competition on the National and International Market

Dutch horticultural production amounted to € 5.4×10^9 in 2007 of which a considerable amount was exported to the European and world market. However, Dutch greenhouse crop production is facing growing competition from countries having favourable conditions for crop production, such as higher light intensities, higher temperature and availability of labour and lower wages. Therefore, many Dutch growers are investigating opportunities or are actually starting production sites outside The Netherlands to make the ultimate market fit with lower production costs. Still, the Dutch environment combining high-tech with high productivity year round together with a well developed infrastructure of the post-harvest chain is still considered favourable for many enterprises.

Chain Integration

Due to the ICT developments, tracking and tracing and customer demands for transparency and fresh products leads to chain-integration and brings producers closer to consumers. Nowadays, value addition shifts more and more to the producers and makes their position stronger. For example, an increasing amount of flowers is sold at the famous Dutch auction through remote image auctioning in which products stay at the production facilities and are not physically present at the auction. Also more and more flowers are being sold by direct mediation between producers and traders. There is a huge advantage in terms of product quality. If the products do not need to be physically sent to the auction, the products will stay fresh longer. In the flowers and vegetables business, direct contracts are made between retail and growers and the trade role of export traders is shifted more and more into a role of facilitator of the transport.

New activities and opportunities growers are facing are putting RFID tags with the products, adding value through packaging, some times in close collaboration with product design and development companies, ICT-tools to give more transparency and information, dedicated sales departments and new distribution solutions. Chain integration is not only going in both forward and backward directions (for example think of tighter collaborations with plant breeders), but also sidewards, creating new products or added value at the same production site. Examples are energy production, CO_2 absorption, water purification and storage as well as projects in a social context.

A GENERIC DESCRIPTION OF THE GREENHOUSE CROP PRODUCTION PROCESS

To be able to analyse the achieved or, for others, the required level of automation in horticultural crop production we first describe shortly the various steps in horticultural crop production. A generic description of the greenhouse crop production process is given in Figure 1. It all starts with the production of seedlings or cuttings. For certain crops, grafting is a necessary step to assure product quality and quantity or prevent diseases. Plants are seeded in substrate or soil plugs and may be transplanted once ore even twice before being planted into or onto the final growing substrate (e.g., soil, rock-wool, perlite, coco fibre, etc.). Before crop production in the greenhouse actually starts, the greenhouse is cleaned or even disinfected. For crops grown in the soil, the soil is disinfected and in some cases a soil profile is prepared for drainage. In the Netherlands vegetables like tomatoes, cucumbers, sweet pepper and egg plant are grown on substrate slabs in a soilless culture. The past ten years, there is a tendency to grow these crops in gullies attached to the greenhouse structure and elevated from the ground. In both cases the soil underneath the substrate slabs and gullies is covered with plastic. In case crops are grown on concrete floors (e.g., ornamentals), only the floors have to be cleaned. Then, the heating system and irrigation system are put in place and the crop is planted. Crop training and maintenance yield a harvestable product. The harvested produce is collected, sorted, and packed before shipment to the auction, trade company or retailer. For single harvest crops like lettuce the production is finished at harvest time. Crop maintenance, harvest and sorting and packing are repetitive tasks for multiple harvest crops likes tomatoes or roses. Depending on the crop grown, a whole production cycle may take a few weeks (e.g., lettuce), several months (e.g., ornamentals, tomatoes, etc.) up to several years (roses). Once production is finished, the remains of the crop are removed from the greenhouse, the greenhouse is cleaned and made ready for the next production cycle.

It is important to note that, in the Netherlands, seedlings or cuttings are produced by highly specialised companies. Essentially, these companies go through the same production cycle as shown in Figure 1, but with a limited cycle time of at most a few weeks.

GREENHOUSE MECHANIZATION: THE STATE OF THE ART

In the face of international competition and to meet the consumer's demand of low cost, high quality and safe horticultural produce, Dutch growers wish to produce as efficiently as possible. As a matter of fact, these requirements are not new in industrial production (e.g., car industry, consumer electronics, etc.). For more than a century, industrial production has gone through a similar process. Industry has dealt with these issues essentially in two ways. First of all, alleviating or even replacing human labour by machines. Secondly, in industry, products are commonly transported through the factory to optimized work cells where workers perform just one or two tasks.

In horticultural crop production lessons have been learned from industry. First of all, tasks are alleviated or human labour is replaced by machines. In Dutch horticultural industry, the state of the art in greenhouse automation largely resembles automation commonly encountered in industry: machines mainly based on mechanical solutions only able to perform exactly the same task over and over again. Examples are machines for automated seeding, transplanting, spacing, grafting, pesticide spraying, sorting and sealing. These machines have in common that they perform relatively simple tasks that do not require much (3D) sensor information and intelligence and do not involve complex manipulations. High-tech mechanization or robots replacing human labour are still hard to find in greenhouse crop production. Secondly, the concept of bringing the crop to the worker is widely used for potted plants for almost 2 decades now.

Some examples that have been implemented the last 5 years will illustrate the state of the art in mechanization in Dutch greenhouse crop production. This overview can be seen as an update of van Henten (2006).

Potrose Cutting Production

A pot-rose cutting production robot, the Rombomatic, has come on the market more then 5 years ago. Using camera vision and industrial manipulators, the machine produces rose cuttings from stock material. Stock material is manually fed into the machine and then processed by a camera-vision controlled industrial manipulator. Cuttings are dipped in root growth stimulating powder and stuck into the soil. The machine can also be used to produce cuttings of some other potted plants. The machine is a small success. Almost 30 robots are daily used in practice.

Grafting

Grafting is a delicate process which requires a high degree of skill and the operation is physically and mentally demanding. A grafting robot was developed by Nishiura et al. (1996). The grafting robot achieved a success rate of 97% at a speed 10 times faster than human workers (Kondo and Ting, 1998). This machine is commercially available and can be used for grafting cucumber, water melon, melon, tomato and egg-plant at a capacity of 800 plants per hour.

Mobile Growing Systems and Internal Transport

Mobile growing systems and internal transport systems have been developed especially for potted plants and seedling production throughout the last two decades. More, recently also cut-flowers (roses, chrysanthemum, lily and gerbera) and vegetables (lettuce, tomato, sweet-pepper) are produced in mobile growing systems, bringing the products to the worker. Many of these products need to be harvested every day (rose, gerbera, tomato). It is questionable whether internal transport of a full productive crop is a favorable option compared with a stationary crop and using advanced logistic systems for transport of harvested produce. It is not (yet) to be expected that mobile growing systems are the solution for the future. Though mobile growing systems may have advantages in terms of management and working environment.

Fruit Vegetable Harvesting

In the past two decades robotics and especially fruit harvesting has received considerable attention in agricultural engineering research. Research prototypes of harvesting robots for tomatoes, cucumbers, egg plant, strawberries have been reported. But until now, none of these machines is commercially available yet. A strawberry harvesting robot is expected to become available in Japan within a few years (Kondo, pers. commun.).

Flower Harvesting

A harvesting machine for roses, shown in Figure 2 is commercially available on the Dutch market. The plants are cut from the beds of a mobile growing system, transported to a buffer system located in the path. A bunching machine located in a central processing area of the greenhouse produces bunches that are dispatched to the auction or retailer. This machine is brought onto the market by Jentjens Machine Fabriek in the Netherlands.

Sorting of Tomatoes, Cucumber, Sweet Pepper

Automatic grading lines for tomatoes (color, weight and diameter), cucumber (weight) and sweet pepper (weight) are commonly used in combination with automated box fillers and stacking machines. New features on the machines are the measurements of sugars and other nutritional components with techniques like spectral imaging and chlorophyll fluorescence.

Sorting of Flowers

Sorting lines consisting of buffered feeders, maturity measurement, length and thickness measurement and automatic bunching and sealing machines are used for sorting roses and gerbera with a capacity of up to 15000 gerberas per hour (gerbera). Through great mechanical achievements human labour has been successfully replaced for the process of putting the flowers in the holes of the carton transportation boxes (Fig. 3). Camera vision is used, but in practice when it comes to accurately assessing the ripeness of the flowers, the systems still rely on human sensing and experience. New developments in sorting roses are focused on assessing the ripeness and quality of flowers automatically. New technologies based on fluorescence technology and 3D measurements to calculate the diameter (cut-anthurium, gerbera, rose) are used in the near future. A rather new Dutch company called Havatec is using X-ray to sort alstroemeria flowers, tulip flowers and tulip bulbs and is using 3D stereo vision for measuring the diameter of the calyx of anthurium (Fig. 4).

FUTURE PERSPECTIVE 1: SUPPORT, AUGMENTATION AND ALLEVIATION OF HUMAN LABOUR

Until 5 years ago most of the high-tech mechanization (grafting, planting, sorting and packaging) was implemented outside the growing area in a controlled area connected to the greenhouse. But until today most work (two thirds of an average production site) is still being done in the growing area where most of the work, maintenance and harvesting of the crop is done in a manual way. Jumping from a fully manual production to fully robotized production is a complex challenge and probably not always the way to go. Therefore technology is implemented to support labour in its task. Research is often focused on the most difficult part of the production process such as harvesting. But until a human can harvest a flower or a vegetable continuously, he has to do a lot of other things. For example: 1. transport himself and his empty buffer; 2. looking for flowers; 3. decide if the specific flower is ripe enough with the actual quality target in his mind for a specific customer, if this reaches all yes then; 4. making access to the product; 5. harvest the product; 6. the harvested product has to be put into a buffer. This step is preferably done blind with a shortest possible handling distance; 7. during the harvest work, labourers are also responsible for other tasks such as reporting plant deceases, instruct new labour, as well as personal maintenance including drinking.

Currently, technical developments are focussed on mechanisation of these other steps within the harvesting procedure first. For these steps, technology is easier to develop and automation of these steps already contributes significantly to an improvement of the efficiency. Last but not least, it is also expected that when all other steps are mechanized; the final step to a fully automated process will be smaller and easier. Some specific examples developed in this direction over the last 5-10 years are listed below.

Intelligent Guided Transport of Buffer and Labour

Intelligent transport systems have been developed to transport labour and storage buffers to and from the growing area. Automatic Guided Vehicles (AGV) can change speed automatically adjusted to the human workload. When the buffer on the AGV is full it will automatically find its way to a place where further handling is done and another AGV is waiting where labour can hop on. A central system is detecting all the AGVs in the production area to monitor logistics and prevent problems. These intelligent AGVs can be found in tomato, rose, gerbera, sweet-pepper and cucumber. But the application will grow in the coming years. Dutch companies who introduced AGVs for greenhouses are: Metazet, Berg Product and Koat (Fig. 5).

Intelligent Buffers

To avoid double handling of the products, products need to be buffered separately and oriented in the right way in as little space as possible, without harming the products. Storing products is preferably done blind and with a shortest possible handling distance so that the worker can focus on the next product while products are stored automatically. Most of the time flowers are put into a temporary bunch so that it is necessary to manually handle the flower twice when sorting or bunching is needed in a next process. In most systems it is not possible to buffer the flowers individually. With information of the AGV it is possible to record the place of the harvested product and a plot of the production-site can be made showing the quantity and sometimes even quality of the harvested product per square meter. In this area companies as Berg Product (Fig. 5) and Koat are experimenting. Solutions are already sold for rose and cucumber.

Intelligent Sensors and Software to Support Human Tasks

With intelligent guided transport it is possible to record the coordinates in the greenhouse where a product is harvested, when sensors are added, such as a load-cel to measure weight of each product, it is possible to measure production capacity on every square meter, but it is also possible to give labour real-time feedback if they harvested the right weight or not, so that workers can adjust themselves. This is already implemented for cucumber by Koat. But in the future it is expected that small vision-systems will measure quality of the products. However, not only the products need to be measured. When an intelligent vehicle can reach every place in the greenhouse, it is also possible to measure climate differences (temperature, humidity, CO_2-level, light), plant diseases with spectral imaging and plant stress. Wageningen UR already developed a sensor that can measure the activity of the photosynthesis of plants, using chlorophyll fluorescence techniques (Ruiter et al., 2005).

Intelligent Motivation to Increase Human Performance

In greenhouse horticulture a lot of the same repetitive tasks are being done by humans. For example in The Netherlands, every day more then 4000 people are harvesting tomatoes year round. It is difficult to find people with a sufficiently good motivation and productivity. Most of the workers come from outside The Netherlands and are staying for a short period, so quite some instruction-time is needed every time new workers arrive. The new generation of workers did not grow up with physical work, but with computers and gaming. Ambient intelligence and techniques from the gaming scene could help low educated workers form the near future to make the work more attractive and more challenging. In a gaming environment people can reach new levels and skills and collect new features. For example, you can reach new levels if your productivity or quality performance increases. If you are doing the primary work well you can teach in new skills, such as reporting plant diseases, giving instructions to others, adding values to the team. On the job you can also collect new features as more salary, working with the newest technology, earlier work stop. Gaming can of course be done individually, but also on a team level and against other teams. In The Netherlands a first experiment with a game called "Work is gaming" was started (Van Leth, 2009). An impression of the game can be found on the internet: www.workisgaming.nl.

FUTURE PERSPECTIVE 2: REPLACEMENT OF HUMAN LABOUR

Prices of the products are not rising with the price of salary. In fact, prices for example of meat tomatoes and chrysanthemums did decline during the past 20 years. A recent study showed that we are also reaching the maximum productivity of a human being when he needs to harvest a single product by hand (Pekkeriet et al., 2007). Given current harvest rates, it is simply not possible to harvest a single product much faster continuously during the whole day. Also the development of more extreme climates in the greenhouse, yielding unfavourable conditions for human labour, requires action to be taken.

However, the International Federation of Robotics (IFR) shows a promise for the future. IFR reports continuous growth of operational robots. In fact, in the year 2008 the number exceeded 1 million operational industrial robots (IFR, 2008). IFR has revealed that robot prices are continuously declining and the performance is improving. This improved price performance ratio makes robots more and more economically feasible alternatives for human labour. IFR statistics show that the real growth is not to be expected in the industrial market, where a specific group of robots needs to be programmed to do all different kind of tasks in the automotive, electrical component, chemical or food industry. The real growth is in the market of field robots, robots for service and domestic use and entertainment and leisure robots. Large groups of robots that are developed to do one or just a few specific tasks and do not need to be programmed by the end user. Also the development in standardized embedded systems, computer vision and software makes development of technology easier and low cost.

We may expect the advent of the next generation machines that will replace humans in the more complex tasks. 3D sensor information, artificial intelligence, complex manipulators and fast and accurate eye-hand coordination are needed to deal with the complex 3D structure of the canopy and the inherent variability amongst the plants in the greenhouse. The presence of the rose cutting robot supports this observation as well as the development of other commercial robots.

FUTURE PERSPECTIVE 3: CHOOSING THE RIGHT DESIGN

Choosing the right level of mechanization for the job(s) to be done is a difficult matter. Analysis of the production process, the material flow, task times, availability and skills of personal and production costs will produce evidence about the opportunities of improving the over-all production process. Project leaders who have know-how about the optimal plant growth and the complex technical implementation are still hard to find. The best designers seem to use only loads of experience and tests. Suggestions for analysis and improvement of production processes can be found in for instance Suzaki (1987, 1993), but in the greenhouse environment a lot of processes are difficult to control. The climate, sunlight and plant structure are different every day with every piece of product. Therefore a lot of knowledge, skill, creativity and above all experience is needed to design better mechatronic solutions. Methods in horticulture mechatronic design are still inadequate and a challenge for the future to improve.

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Figures

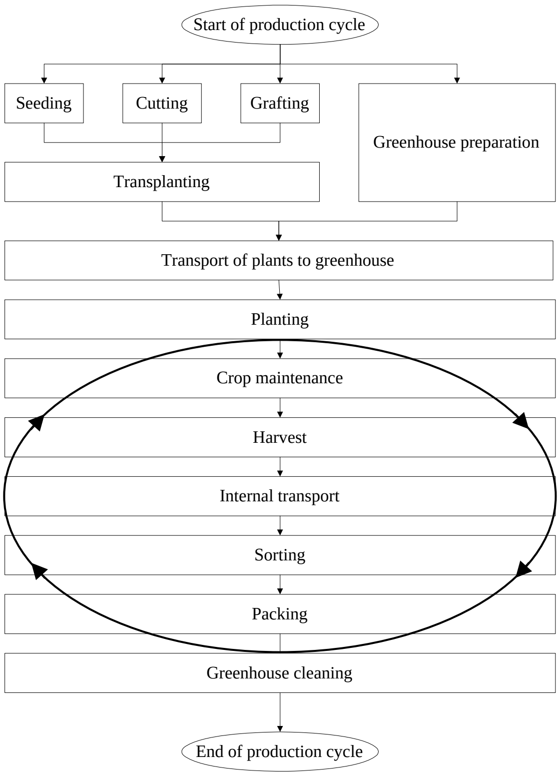

Fig. 1. A generic description of one cycle in greenhouse crop production.

Fig 2. Rose harvesting robot.

Fig. 3. Gerbera sorting and packaging machine.

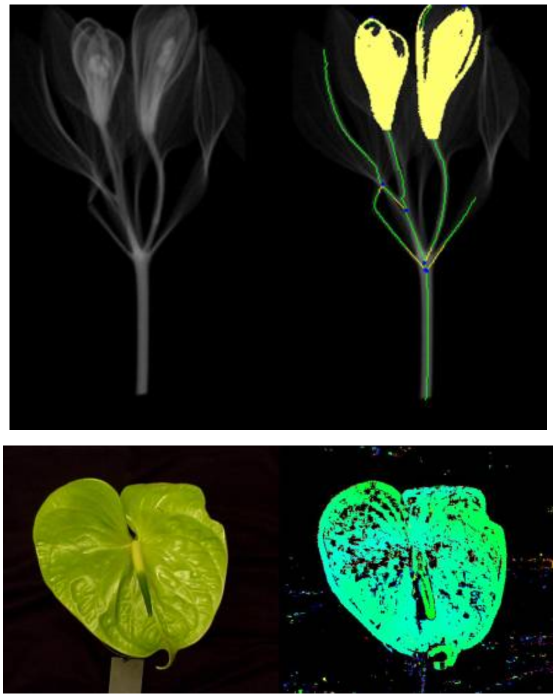

Fig. 4. X-ray sorting (alstroemeria) and stereovision (cut-anthurium).

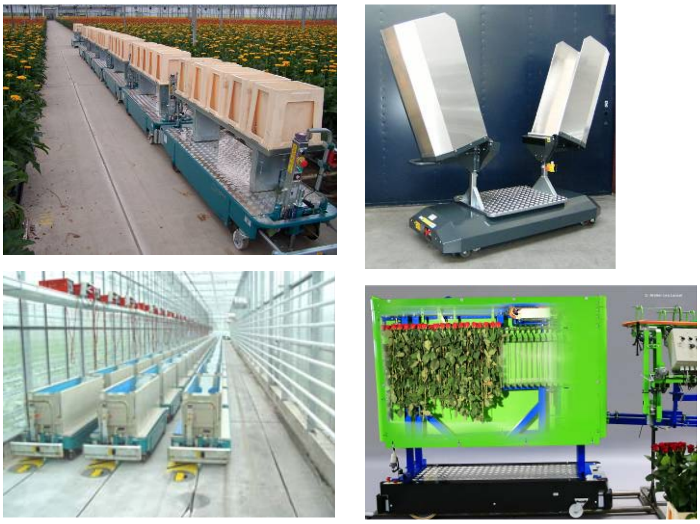

Fig. 5. Intelligent AGVs.