Greenhouse Mechanization: State of the Art and Future Perspective

E.J. van Henten
Greenhouse Technology Group
Agrotechnology & Food Innovations B.V.
P.O. Box 17
6700 AA Wageningen
The Netherlands

Keywords: mechanization, automation, robotics, greenhouse, vegetables, ornamentals

Abstract
This paper reviews the state of the art and future perspective of greenhouse mechanization. Driving forces for mechanization are identified. Dutch greenhouse crop production is used as an example. Analysis of a generic crop production process combined with a review of the state of the art in greenhouse mechanization revealed that the first phases of plant production such as seeding, cutting, grafting and transplanting as well as the final phase of crop production including sorting and packing the harvested produce are mechanised. Those tasks do not require much human intelligence and/or fast and accurate eye-hand coordination. The available machines are largely based on principles of industrial automation consisting of mechanical solutions with only a limited amount of sensors and ‘intelligence’ used. The next ten years, the available line of machines will be redesigned, extended and optimised. The middle phase of crop production including crop maintenance and harvest does not show much automation yet. Maintaining the crop and harvesting do rely on human intelligence and ability and are much more difficult to automate. The next ten years will show the advent of the next generation machines that will be based on the principles of mechatronics and robotics, combining smart mechanical design with sensors and ‘artificial intelligence’ to achieve the fast and accurate eye-hand coordination needed for these difficult tasks. This trend is supported by the commercial development of a strawberry harvester in Japan and a rose harvesting robot and tomato de-leafing robot in the Netherlands. It is concluded that the slow progress in the field of robotic harvesting is to a large extent due to uncertainty in the working environment of the robot as a result of biological variability and the typical structure of the growing systems used. Progress in the field of greenhouse robotics therefore will not only rely on innovations in the field of robot technology but also on necessary innovations in the field of growing systems and plant breeding to reduce variability and thus to simplify the task.

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.

Increasing Size of Production Facilities
In 1990, the greenhouse crop production area in the Netherlands amounted to 10,000 ha, with more than 14,000 companies. In 2002, the production area was still about 10,000 ha, but the number of companies was reduced to about 10,000. So the average size of a commercial greenhouse facility increased from 0.7 ha to 1 ha between 1990 and
Extrapolation of this trend suggests that the average greenhouse size will be about 5 ha in 2030. Which 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 45% of the total production area. And companies with 30 ha of greenhouses are not a rarity anymore.

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 individual consumer groups. As a consequence greenhouse crop production becomes more labour intensive.

High Labour Costs

In Dutch horticultural crop production, labour is the largest cost factor with 34% of the total production costs for vegetables, 27% for cut flowers and 28% for potted plants in 2000 (De Bont, 2001). The past years, labour costs have shown a growing trend.

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 will possibly alleviate this problem on the short term, but the problems with language and education won’t 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 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’s the consumer’s 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 €4.6x10^9 in 2003 of which a considerable amount was exported to the European and world market. However, Dutch greenhouse crop production is facing a growing competition from countries having favourable conditions for crop production, such as higher light intensities, higher temperature and availability of labour and lower wages.

So, summarizing, 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 process of alleviating or even replacing human labour by machines. Also, quality management and the improvement of the over-all efficiency of the production process have received considerable attention in industrial production. It seems worth a while to investigate some answers industrial production has produced to meet the above objectives.
LESSONS LEARNED FROM INDUSTRIAL PRODUCTION

There are two things we may learn from industrial production processes. To improve the production efficiency, the production rate, the product quality and the working conditions, etc.:

- Humans have been given mechanical tools or human labour has been replaced by machines,
- The product (e.g. a car, television or plant) is brought to the worker on a conveyer belt in a work cell where the worker has one or just a very limited set of tasks to perform in a clean and well-organised environment.

In this paper we distinguish two types of mechanization. The first type we will refer to as industrial automation. The second type we will refer to as high-tech mechanization or robotics.

Industrial Automation is Characterized as Follows:

- It replaces a human being or human activity in relatively simple tasks,
- It does not have much flexibility with respect to the task, the objects it has to handle and the working environment in which the machine operates,
- It does not contain many sensors,
- It does not contain much ‘intelligence’,
- It is usually a purely mechanical system.

Robotics or High-Tech Mechanization is Characterized as Follows:

- It is able to deal with more than one different tasks, the system is re-programmable,
- It is flexible with respect to the objects it has to handle and the working environment in which the machine operates,
- It uses many sensors,
- It contains a considerable amount of ‘intelligence’,
- It is based on a combination of mechanics and electronics, or so-called mechatronics.

In practice, one is not able to draw a clear line between these two categories. There is some sort of a grey zone between them in which we will find a blend of industrial automation and robotics.

A GENERIC DESCRIPTION OF THE GREENHOUSE CROP PRODUCTION PROCESS

To be able to analyse the required level of automation in horticultural crop production, we first briefly describe the various steps in horticultural crop production. A generic description of the greenhouse crop production process is given in Fig. 1. It all starts with the production of seedlings or cuttings. For certain crops, grafting is a necessary step to assure production quality and quantity or prevent diseases. Plants are seeded in substrate or soil plugs and may be transplanted once or 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 five 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. Then crop training and maintenance yield a harvestable product. The harvested produce is collected, sorted, and packed before shipment to the auction 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 like 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 Fig. 1, but with a limited cycle time of at most a few weeks.

GREENHOUSE MECHANIZATION: THE STATE OF THE ART

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 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. Main reasons are:

- Reduction of labour costs,
- Optimal use of greenhouse space,
- More efficient centralized processing of the crop (i.e. efficient use of production factors and reduction of emissions),
- Improvement of working conditions because the work cell can be adapted to the worker,
- Monitoring, grading, tracking and tracing during the production process for optimal product quality and safety,
- Opportunity for automation.

Some examples will illustrate the state of the art in mechanization in Dutch greenhouse crop production.

Seeding

Seeding is a highly mechanised process now. A fully automated seeding line consists of a tray washer (capacity of 800 trays per hour), a tray de-stacker (800 trays per hour), a tray filling machine (350 trays an hour), a seeding machine (700 trays per hour), a machine covering the trays, a watering machine (1000 trays per hour) and a tray stacking machine. See Fig. 2 for an impression. For special purposes seed sorting machines are available (20 seeds per second). To improve product quality and uniformity as well as efficient use of the production area, camera assisted tray inspection and filling machines are used to achieve 100% filling with good quality plant material (3000 plants per hour).

Rose Cutting Production

Recently, a rose cutting production robot, the Rombomatic, has been introduced into the Dutch market (Rombouts and Rombouts, 2002). 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 four parallel operating camera vision controlled industrial manipulators (see Fig. 3). Cuttings are dipped in root growth stimulating powder and stuck into the soil. The machine can also be used to produce cuttings of Euonymus, Lavender and Hedera.

Sticking of Cuttings

The development of Geranium and Chrysanthemum cutting sticking robots were reported by Simonton (1990) and Kondo and Monta (1999), respectively. In the
Netherlands a Chrysanthemum cutting-sticking machine was developed and is commercially available. Similar machines are sold in the USA. These machines have capacities of about 20000 plants per hour and easily outperform a skilled human work force. Increased production speed and uniformity of the product quality are main advantages (see Fig. 4 for an impression).

**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, watermelon, melon, tomato and egg-plant at a capacity of 800 plants per hour.

**Robots for Tissue Culture**

A robot for sorting and transplanting of Orchid seedlings in tissue culture was reported by Kaidu et al. (1998) and Okamoto (1996).

**Transplanting**

The development of transplanting robots has been reported by various research groups in the USA (e.g. Yang et al., 1991), Japan (e.g. Sakaue, 1996) and Korea (Ryu et al., 2001). For seedling production, transplanting machines are common practice nowadays. Comparable with seeding machine, a fully automated transplanting line consists of a tray-de-stacker, a tray filler, a transplanting machine with a capacity of 4000 to 20000 plants per hour and a tray stacking machine. Fig. 5 shows the end-effectors of a 12-row plug transplanting machine and a 4-row planting machine for bedding plants.

**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 roses and gerberas are produced at relatively small scale in a mobile growing system. For these crops, a considerable reduction in time needed for the workers to walk through the greenhouse during crop maintenance and harvesting was achieved by using a mobile growing system. Also, improved production control by sorting led to a higher production of roses. And, additionally, the opportunity of automated harvesting was one of the reasons for the introduction of a mobile growing system for roses.

Fig. 6 shows the so-called walking plant system focusing on a highly individualized crop treatment during the production process. Fig. 7 illustrates two mobile growing systems for roses. In one of them, plants are grown on substrate slabs and the whole row is transported through the greenhouse. In the other system, plants are individually grown in plastic containers. Whole rows of containers are moved through the greenhouse, but plants can be sorted and individually treated depending on the stage of growth. Fig. 8 shows various equipment used in bench systems such as bench cleaners, bench fillers, and bench transportation systems.

**Pesticide Spraying**

Automatic in-row pesticide sprayers are commonly used in greenhouse vegetable production. Automatic overhead pesticide sprayers are used during the production of seedlings, flowers and potted plants. See Fig. 9 for examples of in-row and overhead sprayers.

**Attaching Crops to Support Wires or Sticks**

Attaching sweet pepper to the wire is a time consuming task. During the past 5 years a hand-tool was developed, the so-called Ringmaster, shown in Fig. 10, to attach the plants to the wire with a copper ring significantly reducing the amount of labour needed.
for this task. The tool can also be used to attach ornamentals to the wooden supporting sticks as shown in Fig. 10.

**Vegetable Harvesting**

Machines for lettuce and radish harvesting are commercially available. A lettuce harvesting machine is shown in Fig. 11.

**De-leafing Robot for Fruit Vegetables Grown in the High-Wire Cultivation System**

In 2002, a research prototype of a robot for leaf picking of cucumbers grown in the high wire cultivation system was developed and tested with success in a greenhouse (van Henten et al., 2005; see Fig. 12). Based on the promising results of the cucumber harvester and this leaf-picking machine, a commercialisation project was initiated to develop a leaf-picking robot for tomatoes, called Tomation, to appear on the market within a few years.

**Fruit Vegetable Harvesting**

In the past two decades robotics and especially fruit harvesting has received considerable attention in agricultural engineering research (see Fig. 12). Research prototypes of harvesting robots for harvesting tomatoes (Hayashi and Sakaue, 1996; Kondo, 1996; Monta et al., 1998), cucumbers (Arima and Kondo, 1999; van Henten et al., 2002, 2003a,b), eggplant (Hayashi et al., 2001), strawberries (Hatou et al., 2001) 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. comm.).

**Flower Harvesting**

A harvesting machine for Chrysanthemum, shown in Fig. 13, is commercially available on the Dutch market. The plants are cut from the beds, transported to a buffer system located in the path. A bunching machine located in a central processing area of the greenhouse produces bunches that will be dispatched to the auction or retailer. A harvesting robot for roses is currently being developed by Agrotechnology and Food Innovations B.V. and Jentjens Machine Fabriek in the Netherlands and will be available on the market within a few years.

**Sorting of Tomatoes, Cucumber, Sweet Pepper**

Automatic grading lines for tomatoes (colour, weight and diameter), cucumber (weight) and sweet pepper (weight) are commonly used in combination with automated box fillers and stacking machines.

**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 with a capacity of up to 9500 roses per hour (see Fig. 14 and 15 for examples). 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.

**CHOOSING THE RIGHT LEVEL OF MECHANIZATION FOR THE JOB(S) TO BE DONE**

Choosing the right level of mechanization for the job(s) to be done is a difficult matter and the choice will depend on conditions such as those listed at the beginning of the paper. 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 overall production process. Sometimes small changes in process flow or handling may result in significant reduction of labour required. Suggestions for analysis and improvement of production processes can be found in for instance Suzuki (1987, 1993).
GREENHOUSE MECHANIZATION: FUTURE PERSPECTIVE

Having reviewed the state of the art in greenhouse mechanization and looking at Fig. 1 again, it is interesting to note that especially the first phase of greenhouse crop production, i.e. seedling production and planting, and the final phase, i.e. sorting and packing and to a lesser extent harvesting are mechanised. The second phase, crop maintenance, is hardly mechanised. Essentially, the relatively simple tasks are mechanised using principles from industrial automation. The tasks that are not yet mechanised in the first, second and third phase of the production process usually require special human skills. Or to put it in a different way, these tasks are also difficult for humans. These tasks require the ability to process large amounts of sensor information about size, shape, colour and especially position in the 3D space and very fast and accurate eye-hand coordination to finish the task as efficiently as possible. Most of the crop maintenance tasks as well as some of the stages in the grading and packing of vegetables and flowers belong to that category.

So, what can we expect in the near future of say the coming 5 to 10 years? Clearly, the available machines will be redesigned and optimised to perform better in terms of speed and quality. Growers and their suppliers have a very innovative attitude. So, we may expect ‘quick-wins’ by the introduction of mechanical tools and machines to quickly solve bottle-necks encountered in greenhouse crop production. But these will come more or less as a surprise and will heavily lean on industrial automation technology. Also, 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 grafting robot and the rose cutting robot support this observation as well as the development of commercial robots for strawberry harvesting, rose harvesting robot and de-leafing of tomatoes. However, major technical innovations usually take 5 to 10 years or even longer from initial idea to market introduction. So, it is not reasonable to expect revolutionary technical innovations on the market if the signs are not yet visible in agricultural engineering R&D unless major changes in the way crops are produced take place for reasons not known at the moment.

The next decade, we may expect more new or renewed initiatives in the field of robot crop maintenance and harvesting. But progress in that field will not only rely on better mechatronic sensing and control hardware and software to achieve the fast and accurate eye-hand coordination needed to successfully and efficiently fulfil such tasks. Simplifying the task at hand will allow for much faster progress in that field. It is interesting to note that the majority of operational autonomous robots are currently being used in the automotive industry, the industry for consumer electronics and labs. In these applications the work cell does not contain much uncertainty, each car or television has a fully and exactly defined shape and size. Also, the working environment is clean and does not contain any unknown obstructions. Such conditions also explain the success of robotic grafting systems and the rose cutting robot and transplanting machines. The main bottleneck in for instance robotic fruit harvesting is the unstructured environment due to biological variability and the structure of the growing systems used. To simplify robotic harvesting, the biological variability needs to be reduced and/or new more structured growing systems need to be adopted. This explains the success of the cucumber harvesting robot and the de-leafing robot for which a new cultivation system was adopted, the high wire cultivation system. In that cultivation system, the crop is less dense, fruits and stems are easily detected and fruits are easier to approach (van Henten et al., 2002, 2003). It is expected that the next generation machines will be the result of combined innovations in the field of robot technology, cultivation systems, plant physiology and plant breeding.
ACKNOWLEDGEMENTS
The invitation by the organizing committee of the MARDI-ISHS International Symposium on Greenhouses, Environmental Controls and In-house Mechanization for Crop Production in the Tropics and Sub-tropics to present this material as a keynote presentation is gratefully acknowledged. The author also wishes to thank his colleagues Jan Bontsema, Erik Pekkeriet, Bart Van Tuijl, Erik Van Os and Jochen Hemming for inspiring discussions on the various aspects of greenhouse mechanization and robots for greenhouse crop production.

Literature Cited


Figures

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

Fig. 2. A seeding line consisting of the EC-40 tray filler, the PSL-2 seeder, the SB-40 tray covering machine and AMS 40-60 watering machine of Visser ITE, The Netherlands.
Fig. 3. The rose cutting and sticking machine Rombomatic of Jentjens Machinetechniek B.V., The Netherlands.

Fig. 4. Various stages during automated Chrysanthemum cutting sticking (Visser ITE, The Netherlands).
Fig. 5. Four-fingered grippers of the 12-row plug transplanting machine (left) and four row planting machine for bedding plants by Visser ITE, The Netherlands (right).

Fig. 6. A mobile growing system, the so-called walking plant system, of Metazet, The Netherlands.

Fig. 7. Mobile growing systems for roses of Van Zaal, The Netherlands (left) and Hawe (without plants), The Netherlands (right).
Fig. 8. Bench transportation machine (top left), bench filling machine (top right), plant handling machine (bottom left), bench washer (bottom right) of HAWE, The Netherlands.

Fig. 9. An automatic in-row pesticide sprayer of Berg Produkt, The Netherlands (left) and an automatic overhead pesticide sprayer of Visser ITE, The Netherlands (right).
Fig. 10. The Ringmaster of Priva B.V., The Netherlands, used for attaching vegetable plants to the support wire (sweet pepper) or to supporting sticks (ornamentals).

Fig. 11. A lettuce harvesting machine of Fraeye BVBA, Belgium.

Fig. 12. Research prototypes of robots for harvesting (left) and de-leafing (right) of cucumbers grown in the high wire cultivation system of Agrotechnology and Food Innovations, The Netherlands.
Fig. 13. The Chrysanthemum harvester and bunching machine of BTM, The Netherlands.

Fig. 14. A rose grading and bunching machine of Jamafa, The Netherlands.

Fig. 15. A rose bunching (left) and sealing machine (right) of Aweta, The Netherlands.