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Hortibot: Feasibility study of a plant nursing robot performing weeding operations – part IV

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***Abstract*.** Based on the development of a robotic tool carrier (Hortibot) equipped with weeding tools, a feasibility study was carried out to evaluate the viability of this innovative technology. The feasibility was demonstrated through a targeted evaluation adapted to the obtainable knowledge on the system performance in horticulture.

A usage scenario was designed to set the implementation of the robotic system in a row crop of seeded bulb onions considering operational and functional constraints in organic crop, production. This usage scenario together with the technical specifications of the implemented system provided the basis for the feasibility analysis, including a comparison with a conventional weeding system. Preliminary results show that the automation of the weeding tasks within a row crop has the potential of significantly reducing the costs and still fulfill the operational requirements set forth.

The potential benefits in terms of operational capabilities and economic viability have been quantified. Profitability gains ranging from 20 to 50% are achievable through targeted applications. In general, the analyses demonstrate the operational and economic feasibility of using small automated vehicles and targeted tools in specialized production settings.

Keywords. Feasibility study, Plant Nursing Robotics, weeding, agriculture, horticulture, capability, economic viability

Introduction

Within outdoor organic gardening, weeds are today a major problem, especially for crops, like carrots and onions. Also, there is an increasing demand from the consumers and the society to reduce the pesticide use in order to minimize the impact on flora, fauna, aquatic system, and working environment. The pesticide may be reduced by using precision spraying or the pesticide use may be eliminated completely by using manual weeding within the rows. The manual weeding may be carried out in an upright working position using a hoe, lying on the knees or positioned on a cart. All working postures will be strenuous, even for a short duration and the work may be characterized as one-sided and repetitive. Depending on the weed intensity, Danish outdoor gardeners use 50-300 hours per hectare for manual weeding in onions and carrots (Ørum and Christensen, 2001; Melander and Rasmussen, 2001). This is cost-intensive not only in direct labour costs but also in form of labour allocated to this one operation relative to other urgent tasks within the growing season. Further, there are often difficulties associated with procuring the necessary labour.

Automation of the precision spraying or the manual weeding will eliminate the monotone and fatiguing work and replace it with a precise, quality enhancing and flexible machine operation. Experiences from the use of auto steering shows that the working conditions of the operator is improved significantly in terms of reduced strain and improved work quality (Keller, 2005). The natural next step will be to make the machine or implement autonomous and release the operator for concurrent tasks like managing the operation. Mobile robots have emerged as automated guided vehicles (AGV's) situated in structured environments. Currently, these types of vehicles are developing into autonomous vehicles capable of self-guidance comprising reliable and autonomous navigation in unstructured environments (Garcia-Alegre, 2001). These vehicles are very much suited for replacing tedious and monotonous tasks in industry and agriculture requiring precision, reliability, traceability, *etc*. Their applicability and superior performance have been proven through extensive use in the industrial setting (*e.g*. Mortimer, 2004). They have definite cost, quality, workability, and output advantages over manual processes even for processes where labour costs are low because of the higher work quality. Overall productivity may be increased even if the proverbial rule of 80/20 applies, where only 80% of the task at hand is fully automated (Stentz, 2001).

As regards relevant weeding robots, worldwide, there exists only a few today. In Denmark, there is a prototype GreenTrac, which is designed as an environmentally sensible tool carrier for organic outdoor gardeners. The GreenTrac is not matured for production and is unnecessary big for most tasks (Sørensen and Frederiksen, 2002). In Sweden, there is a robot for intra row weeding in sugar beets (Åstrand and Baerveldt, 2002). Israel has a multi-functional prototype robot for transplanting and spraying (Edan and Bechar, 1998). In England, an outdoor gardening robot has been developed which is capable of passing over parcels of row crops (e.g. Hague, 1997), but it has difficulties performing real field work. At the latest, Aarhus University, Department of Agricultural Engineering, and Vitus Bering, Denmark, have been involved in developing an automatic tool carrier, (www.Hortibot.com) based on an existing commercial machine (Jørgensen et al., 2006a; Jørgensen et al., 2006b).

The paper presents the feasibility of using the Hortibot to carry weeding tools within organic grown onions. The potential economic effects of changes in the use of technology for row crop weeding were assessed by using the principles of a partial budget approach (Landers, 2000). The focus was on demonstrating the difference in operating costs between the dedicated innovative technology and the conventional system.

Three accompanying papers were presented at ASABE2006, part I to III, covering the following project related subjects: I - Solutions chosen for the HortiBot with regard to hardware mechanical-electrical interfaces and software; II - Application of Quality Function Deployment (QFD) Method for Horticultural Robotic Tool Carrier Design Planning; III - HortiBot: Comparison of potential present and future phytotechnologies for weed control.

Methodology

In order to assess the operational and economic viability of a robotic weeding system, a usage scenario for a typical horticultural weeding operation was set up. This scenario was then analyzed and evaluated using dedicated evaluation methods. The usage scenario was analysed in terms of operations performance and operating costs. The costs and potential benefits of using autonomous vehicles were compared with conventional operations and the supplemented management practices.

Usage scenario

The devised scenario is for organic cultivated bulb onion (*Allium cepa L.*) and shallots (*Allium cepa L. var. aggregatum* G. Don). The used onion seeds, accepted by regulatory authorities for organic onion production, have an expected germination rate of 75%.

Seeding are done on 2 m wide beds made up of loosened soil, and seeded in 5 parallel rows per bed with 35 cm row spacing and 3 cm seed spacing within the row. The cultivation and seeding procedures are recommended by the Danish Agricultural Advisory services for organic grown onion (Ørum & Christensen, 2001). The headlands are not cultivated, and the positions of obstacles are known and clearly marked in the field according to prerequisites set by the HortiBot operation manual (Jørgensen et al., 2006). As regards the expected weed population in the horticultural field, it consists of commonly appearing species of monocotyledons and dicotyledons of annual, perennial weeds and perennial weeds with vegetative reproduction.

Selection of tool carrier technology

By modifying a remote controlled slope mower it has been shown that it is possible to produce a robust horticultural tool carrier called Hortibot (Jørgensen et al., 2006a; Jørgensen et al., 2006b) – see Figure 1.

The HortiBot is capable of passing over several parcels with visible rows autonomously based on a new commercial row detection system from Agrocom Vision (former Eco-Dan Inc., Denmark) with minimum use of Global Positioning Systems (GPS). Other functionalities include that unskilled workers will be able to operate the basic functions of the HortiBot with a minimum of training and by using a pictogram as an operational guide. Traceability in the Hortibot will be available online and in real time by transmitting all operational data to an internet based database.

It was shown that the most important user requirements attained to a robotic weeding tool carrier include easy adaptation of the carrier to field conditions in terms or row distance and parcel size (Sørensen et al., 2006). Currently, the Hortibot does not fulfill these demands entirely, but the modular construction makes it relatively simple to adapt to these requirements. Furthermore, a project named Omnirota at the Aarhus University, Denmark, will fully develop and mature a basic wheel module targeted at a flexible and High-Tec robot platform adapted to operations in agriculture and horticulture. Such a module, which can be implemented across robot platforms will rationalize and considerably advance the development of the robot platforms themselves.

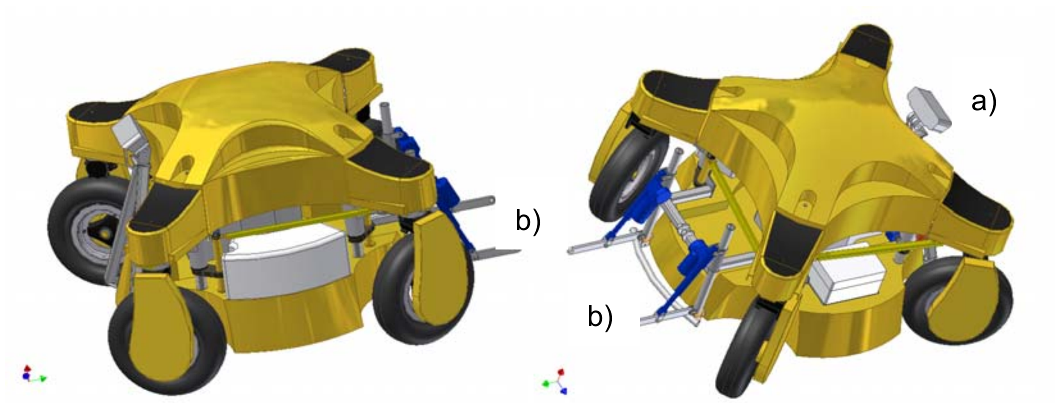

Figure 1. Hortibot design with individual wheel control, 3D row vision system (a), and lift arms (b)

Selection of physical weeding technology and strategy

In this scenario, flame weeding is not considered because of some significant weed controlling and practical drawbacks. Firstly, weeds have to be at earlier growth stages than the crop (Bond and Grundy, 2001), and secondly, the most frequently occurring weeds, pineapple-weed (*Chamomille suavéolens*), is tolerant to thermal treatment (Netland et al., 1994). Nemming (1993), Holmøy and Netland (1994) and Netland et al. (1994) reported that flame weeding at the time of post emergence of onions provides a large variation in weed density reduction (i.e. between 40 and 90%) without affecting crop yield, and where the selectivity depends on the dose (kg gas ha^{-1}). Unlike mechanical methods of weed control, there is no soil disturbance to stimulate a further flush of seedling emergence. In addition, flame weeders have the advantage of being usable when the soil is too wet for mechanical weeders. Nevertheless, flame weeding is not considered for robotic weeding mainly due to safety and auxiliary reasons, meaning that more supervision is required for flame weeding than for mechanical weeding.

Instead, the selected strategy was to use a standard and 2 m wide weed harrow mounted on the HortiBot for weeding 0 to 3 weeks before seeding which should be approximately 1 week after bed ridging (the HortiBot navigate on the basis of computer vision recognition of the topography of the tracks between beds). The weed harrowing procedure is repeated 1 to 3 weeks after seeding. The forward velocity for weed harrowing is 1.5 m/s.

The implement tools for inter and intra-row weeding consists of standard A-shaped hoes for inter-row weeding, and with bed ridgers attached to each end of the implement tool bar. The intra-row weeding will be provided by finger and torsion weeders and pneumatic nozzles (Bernaerts, 2004; Lütkemeyer, 2000), all attached to five individual units carrying the A-shaped hoes. The pneumatics operates at 4-8 bar and output 2 m^3 compressed air, and distributed on 10 nozzles (2 per row) placed 2-3 cm below soil surface and blowing on weeds in order to up-root or damage them. The pneumatic nozzles are switched on and off by electronically controlled pneumatic valves. This feature has not been researched yet, but the technology is simple and hence, it is selected for this scenario and occupying a forward velocity of 0.5 m/s. Both the navigation control parallel to the rows and with-in rows are based on computer vision recognition and furthermore, the positioning of individual onion plants are based on principles described in Åstrand et al (2005), as this method is not restricted to a specific crop. Åstrand et al. (2005) showed that context based recognition of sugar beets (*Beta vulgaris* L.) at the 2-leaf stage obtained an individual crop recognition rate of 96%. Thus, a crop loss of 4% is expected but only for the first treatment, as the method gets more reliable when weeds are at earlier growth stages than the crop. Since seeded onions do not have 100% field emergence, Åstrand et al. (2005) also defined that about 30% weed seedlings in the row will be recognized as onion at crop field emergence rate of 70%, and stated that the higher crop emergence, the less weeds recognized as crop plants.

Figure 2. Selected weeding tool (www.mechanischschoon.nl)

By utilizing more advanced computer vision navigation, a row band width of 5 cm is considered for the boundary between inter and intra-row weeding area (2.5 cm on each side of the row center defined by plant positions). Thus, in this scenario it is expected that 87.5% of the total area are covered with the inter-row area and the inter-row weeding, leaving 12.5% for the intra-row area for intra-row weeding. A strategy consisting of 6 to 8 post-emergence treatments with 1 to 2 weeks apart are considered as recommended by Graglia et al. (2004, 2006). A 60-95% weed control is expected for the intra-row area (Bernaerts, 2004, www.mechanischschoon.nl) and 62-90% weed control (all species) is expected for the inter-row area (Graglia et al., 2004, Pullen and Cowell, 1997).

The conventional strategy is selected according to the newly published manual for practical weed control (van der Schans and Bleeker, 2006), which implies weed harrowing with e.g. a 5 bed wide tine harrow (i.e. 10 m) 0 to 3 weeks before seeding which should be approximately 1 week after bed ridging. The weed harrowing procedure is repeated 1 to 3 weeks after seeding. Post-emergence treatment will consist of a combined 3 bed treatment with A-shaped sweeps, finger and torsion weeders. Three treatments, 1 to 2 weeks apart are performed. Commercial available computer vision systems will be used for navigation at 2 m/s operation velocity, leaving the row band border at +/- 5 cm from the row center (i.e. row band width = 10 cm). Surviving weeds in the intra-row area are hand weeded once after all three tractor operated operations are carried out. An overall weed control of 95% is expected with the conventional strategy.

Operations modelling

The performance estimate for the autonomous weeding unit and the conventional system was modeled using a framework of specific task models (Nielsen & Sørensen, 1993; Sørensen *et al*., 2003). According to this framework, labour and machine input was estimated as a function of parameters, such as field dimensions, working speed, working width, etc.:

$$A = 60 / \left(\frac{600 \times h}{v \times e} + \frac{p \times b \times n}{e \times (1+a)} + k + s \times h \right) \times h^{-1} \qquad (1)$$

where: *A* is the realised capacity in ha h^{-1}; *h* is the size of the field in ha; *v* is the working speed in km h^{-1}; *e* is the effective working width in m; *p* is the time for turning in min per turning; *b* is the field width in m; *n* is the number of turnings per pass (normally *n*=2); *a* is a model parameter dependent on field shape and travel pattern (*a*=1 in the case of driving back and forth in the rows); *k* is the turnings on headland in min per field; and *s* represented the stochastic crop and soil stops, adjustments, control, tending of machine in min ha^{-1}.

The field efficiency factor depicts the realized capacity to the theoretical capacity. In terms of Equation (1), the field efficiency, *E*, is estimated as:

$$E = \frac{v \times e}{10 \times h} / A \qquad (2)$$

Typical values for field operations vary from 55 to 90% with typical values for weeding operations ranging from 70 to 90% (ASAE, 2003).

Operating costs

The direct costs of operating new technologies were calculated by using conventional methods for estimating depreciation, interest and maintenance of machinery (Sørensen et al, 2005). The costs were distributed over a predetermined lifetime as well as over the number of hectares being treated by the machinery. The machinery costs included interest and depreciation, maintenance, fuel consumption and necessary manual labour input.

Maintenance and repair costs per hour included costs for both materials and labour, and were based on normative data for maintenance costs derived as a fraction of the initial investment and depending on the yearly use of the machine (Laursen, 1993). In this way, the variation as a function of machinery size was reduced. This procedure was used for both implements and tractive machinery.

The average fuel requirement per hour was estimated as a function of machinery size. In order to assure equal assumptions across the systems, the average engine load for all machinery systems was set to the same fraction of the maximum power. The average fuel consumption was estimated as:

$$l = \frac{x \times P_m \times f_e}{1000 \times d} \qquad (3)$$

where: *l* was the average fuel consumption in *l* h^{-1}; x was the engine load; p_m was the maximum power of the tractor in kW, f_e was the assumed fuel efficiency in g kWh^{-1}, and *d* was the density in kg l^{-1}

The annual costs of interest and depreciation were estimated as an annuity distributed over the economic life of the machine. The economic life was dependent on the annual utilization of the machine, such that more operating hours had a faster depreciation rate. In addition, a maximum economic life span was estimated for each machine as a limit not to be exceeded even if the annual utilization of the machine was low. A general scrap value of 10% was anticipated, indicating that the used machines were saleable (Laursen, 1993). The interest rate was set to 5% as representing a current average rate.

Labour costs were based on contractually fixed hourly wages (Sørensen *et al*., 2003), and the number of operating hours was based on the labour requirement estimations.

The average annual total costs were determined using Eqn (4) as a combination of capital costs and variable costs:

$$C = \frac{(I - I \times S_n / (1+r)^n) \times r}{1-(1+r)^{(-n)}} + o \times (m + w + t) \qquad (4)$$

where: C was the total annual costs in \$ year^{-1}; I was the initial machinery investment in \$; S_n was the scrap value after n years in decimal; n was the number of years over which the machine was depreciated; r was the interest rate in decimal; o was the required operating hours; m was the maintenance costs in \$ h^{-1}; w was the labour costs in \$ h^{-1}; and t was the tractor costs in \$ h^{-1}; The number of operating hours was estimated as a function of the acreage and the machine capacity.

Results

Operational parameters

The model parameters are based on preliminary test data and expert assessments. Table 1 lists the assessed parameters for the operational performance, workability constraints, number of individual operations, and the initial investment.

Table 1. Operational parameters and model prerequisites for robotic weeding

Operational parameters	*Defined value*
Basis tool carrier platform:	Hortibot system
- v (inter and intra row weeding), m s^{-1} [#)]	0.5
- v (weed harrowing, m s^{-1} [#)]	1.5
- e (effective working width), m [#)]	2.12
- p (turning time), min turning^{-1} [#)]	0.41
- b (field width), m [#)]	158
- s (stops and control), min ha^{-1} [#)]	18.0
- h (field size), ha [#)]	5
- field shape [#)]	1:2
- service time, % [¤)]	15
- seasonal period [$)]	15. April – 15. July
- number of treatments per season [£)]	8
- supervising, % of operating time [@)]	50
Investment	$
Basic tool carrier: [α)]	
- wheel modules	21818
- generator	7272
- navigation cameras	4545
- carrier frame	5454
- central control and navigation computer	3636
- D-GPS	3636

Weeding tool: [§§)]	
- spring-tine harrow, 2.12 m working width	2370
- hoe, 5 rows	9665
- computer vision cameras (3 units a 1818 $)	5454
- basic computer platform (PC/104)	727
- compressor unit (extreme 3-24 VDC)	1073
- air valve manifold	55
- electrical valve control (10 units a 59 $)	590
- nozzles (10 units a 44 $)	440
- sideshift unit (electric actuator)	727
- torsion weeder (79 $ per row)	395
- finger weeder (1340 $ per row)	3636
Total investment	71493

[#)] The denoted parameters according to Eq.(1) and quantified/modified from (Nielsen & Sørensen, 1993)
[§)] The estimated capacity according to the assessed intra-row working speed
[")] The estimated capacity according to the assessed inter-row working speed
[¤)] The service time includes work time allocated to maintain the robotic system analogous to conventional field operations (Sørensen et al., 2005)
[$)] The length of the growing season susceptible for weeding operations was determined from van der Schans et al. (2006)
[£)] The treatments consisted of 2 x hoeing before emergence and 6 x combined inter-row hoeing and intra-row weeding after emergence
[@)] The task of supervising the robotic weeding system was estimated as amounting to 50% of a persons total work time
[α)] The prices are based on experiences from prototype development (e.g. Jørgensen et al, 2006)
[§§)] The prices are based on Bowman (2002), Wested Industrial Automation Inc. and MB-Technique Inc.,

The comparing conventional system consists of a tractor based system with implements like spring-tine harrows and row guided hoes. The conventional system is modelled by assessing a number of technical and operational parameters – see Table 2.

Table 2. Operational parameters and model prerequisites for conventional system

Operational parameters	*Defined value*
Basis tool carrier platform:	Tractor
- *v* (intra row weeding), m s^{-1} [#)]	1.66
- *v* (weed harrowing), m s^{-1} [#)]	1.94
- *e* (effective working width), m [#)]	6.3
- *p* (turning time), min $turning^{-1}$ [#)]	0.41
- *b* (field width), m [#)]	158
- *s* (stops and control), min ha^{-1} [#)]	6.28
- *h* (field size), ha [#)]	5
- field shape [#)]	1:2
- service time, % [¤)]	15
- seasonal period [$)]	15. April – 15. July
- number of treatments per season [£)]	6
Investment [α)]	$
Basic tool carrier:	
- tractor (75 kW)	63636
Weeding tools:	

- spring-tine harrow, 10 m working width	12987
- hoe, 15 rows – 6.3 m working width	12454
- ECO-DAN guidance system	9090
Total investment	98167

#) The denoted parameters according to Eq.(1) and quantified/modified from (Nielsen & Sørensen, 1993)
¤) The service time includes work time allocated to maintain the system (Sørensen et al., 2005)
%) The potential workable hours per day is set conform with normal working hours for the operator
$) The length of the growing season was defined as in Table 1
£) The treatments consisted of 2 x hoeing before emergence and 4 x inter-row hoeing after emergence
α) The prices are based on Agrimach (2004)

Comparative analysis

By using the described methodologies for operational performance and costs, a comparison was carried out for the robotic system and the conventional system. The basic assumptions for the comparison involve that the two systems are utilized to their fullest based on the respective system capacities. The results are shown in Table 3.

Table 3. System comparison

	Robotic system	Conventional system
Operational performance:		
- capacity (tine weeder), ha h^{-1} [“)]	0.74	4.67
- capacity (inter-row hoe), ha h^{-1} [§)]	0.31	2.36
- operation hours per day [%)]	16	8
- workable operations days [&)]	50	50
- operation hours per season	800	400
- annual treated area, ha	36.5	188.4
- weeding efficiency, %	90	95
Cost decomposition:		
- depreciation and interest, \$ ha^{-1}	253	41
- maintenance, \$ ha^{-1}	626	38
- fuel, \$ ha^{-1}	22	20
- manual weeding, \$ ha^{-1}	241	3010
- operator wage, \$ ha^{-1}	229	44
- supervision, \$ ha^{-1}		
- preparation, \$ ha^{-1}	69	7
Total costs, \$ ha^{-1}	1737	3164
Cost reduction, %	54	

“) The estimated capacity according to the assessed inter-row working speed
§) The estimated capacity according to the assessed intra-row working speed
%) The potential workable hours per day for the robotic system are set by an assessment of light constraints, necessary service work – see also Pedersen et al (2006). The workable time per day for the conventional system is constrained within normal working hours for the operator
&) The potential number of days suitable for hoeing and weeding was estimated yearly over the 30-year period of 1961–90 using recorded weather data together with the weather constraints determining the number of workable days or hours derived from reported conditions for soil tillage in Denmark (Sørensen, 2003).

The model comparison shows a cost reduction of 35% by using the robotic weeding system with the denoted prerequisites, like 90% weeding efficiency as an expression for the work quality. Preliminary sensitivity analyses indicate that a 75% weeding efficiency will reduce the profitability by 26%.

Other important factors influencing the profitability of the robotic weeding system include the initial investment and operational costs like maintenance costs. By reducing the initial investment by 25% the profitability of the robotic weeding system is improved by 13%. In the basis scenario, the maintenance costs for the robotic system is estimated using norm data for a conventional combine harvester as illustrative of a comparatively complex machine. In the case of using maintenance norm data for tractors, the profitability will increase 28%. Further sensitivity analyses are required to precisely identify the most significant factors in terms of influencing the profitability of the robotic systems as compared with the conventional system.

Conclusion

The study shows that autonomous inter-row and intra-row weeding systems have the potential becoming more economically viable when compared to conventional tractor operated weeding systems combined with manual weeding. Important determining parameters for the profitability of the autonomous system are the work quality in terms of weeding efficiency, initial investment, and operational costs like maintenance costs.

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