HortiBot: A System Design of a Robotic Tool Carrier for High-tech Plant Nursing

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ABSTRACT

Danish organic outdoor gardeners today use 50-300 hours per hectare for manual weeding. Through automatic controlling of an existing commercial machine this often heavy and cost-consuming weeding will be eliminated. At the same time, a fully-automatic registration of field activities will contribute to the efficient implementation of EU directive 178/2002 concerning traceability in the primary production and thereby enhance the food-safety in the production chain. A radio controlled slope mower is equipped with a new robotic accessory kit. This transforms it into a tool carrier (HortiBot) for high-tech plant nursing for e.g. organic grown vegetables. The HortiBot is capable of passing over several parcels with visible rows autonomously based on a new commercial row detection system from Eco-Dan a/s, Denmark. This paper presents the solutions chosen for the HortiBot with regard to hardware, mechanical-electrical interfaces and software. Further, the principles from a Quality Function Deployment (QFD) analysis was used to carry out the solicitation, evaluation and selection of most qualified design parameters and specifications attained to a horticultural robotic tool carrier. The QFD analysis provided a specific measure to evaluate each selected parameter in terms of satisfying user requirements and operational performance aspects. Based on a combination of importance rating and competitive priority ratings important user requirements include easy adaptation to field conditions in terms of row distance and parcel size, profitability, minimum crop damage during operation, and reliability. Lesser importance was attributed to affection value, attractive look, the possibility of out of season usage, and the use of renewable energy.

Keywords: Machine design, machine specifications, Quality Function Deployment (QFD), robotics, tool carrier

1. INTRODUCTION

Within outdoor gardening, weeds are today a major problem, especially for early sown or transplanted crops with a slow growth rate, like carrots and onions. Weed control can either be in the form of mechanical inter row combined with intra row pesticide application (90% of the total outdoor gardening area in Denmark) or mechanical inter row combined with manual intra row weeding (10% of the total outdoor gardening area in Denmark). There is however, 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.

Depending on the weed intensity, Danish outdoor gardeners use 50-300 h/ha for manual weeding in onions and carrots (Ørum and Christensen, 2001; Melander and Rasmussen, 2001). This is cost-intensive not only in direct labor costs but also in form of labor allocated to this one operation relative to other urgent tasks within the growing season. Further, there are often difficulties associated with procuring the necessary labor.

1.1 Robots within Plant Production and Outdoor Gardening for Weed Control Today

With regards to relevant weeding robots, worldwide, there exists only a few today. In Denmark, there is a prototype called GreenTrac, which is designed as an environmentally sound tool carrier for organic outdoor gardeners. Currently, 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 et al., 1997). However, it cannot perform proper field work.

1.2 Today's Technological Barriers

The majority of agricultural prototype robots base its navigation on high precision satellite position systems, and on field and crop maps. Hence, it is relatively information demanding and complex to work with. From the operator viewpoint, commercialization of a field robot requires that it is significantly simpler to operate (Callaghan et al., 1997; Jørgensen, 2005).

A technological development of weeding robots depends, apart from the market situation, to a great extent on technological barriers and comparability with the existing technological stage. Kassler (2001) lists barriers that have retarded the exploitation of computer-controlled machines in agriculture, e.g.: Insufficiently robust mechanical technology; Costly mechanical technology; Limited capability; Basic knowledge to create technology as dexterous or as skilful as that of a trained worker is currently unavailable.

1.3 The Voice of the Customer

Within the concept of Total Quality Management (TQM), a number of tools have been adapted to assist the process of customer driven planning and engineering for product development (Cohen, 1995). One such tool is the Quality Function Deployment (QFD), which has as its primary goal the translation of customer requirements into technical requirements of each stage of the product design and production (Chan and Wu, 2001; Crowe and Cheng, 1996). The process involves identifying customers' requirements for a product (WHATs), customers' view on the relative importance of these requirements and the relative performance of the intended product and the main competitors on these requirements. Also, the complete QFD process includes translating the customer requirements into measurable engineering requirements (HOWs) through careful evaluations performed by technicians recognizing the relationships between customer requirements and engineering characteristics.

1.4 Aim and Deliverables

The consumer driven demands to reduce the pesticide usage increases the demand for mechanical weed control as a way to avoid costly hand weeding. Within a few years, new environmentally sound technologies are expected to replace hand weeding. However, this creates a demand for a mechanical unit which will be able to carry future high precision weeding tools with a low constant speed and high precision.

The aim of this paper is to describe a developed robust horticultural robot called HortiBot, which will have the following main characteristics:

- Capable of passing over several parcels with visible rows autonomously based on a commercial row detection system with no or minimal use of Global Positioning Systems (GPS).
- Unskilled workers will be able to operate the basic functions of the HortiBot followed by attending one hour of training.
- All operational data is automatically sent to an internet based database.
- The operation of the HortiBot is documented in terms of feasibility, operational capacity, and economy.

Further, the objective is to identify qualified user requirements for the design of a robotic tool carrier to be used carrying various implements for plant nursing.

1.5 Safety Emphasis

Through automatic regulation of an existing commercial machine, heavy and cost-consuming weeding is eliminated. Further, fully-automatic controlling will contribute to the efficient implementation of EU directive 178/2002 concerning traceability in the primary production and thereby enhance the food-safety in the production chain.

2. MATERIALS AND METHODS

The project is coordinated by The Danish Institute of Agricultural Sciences, Department of Agricultural Engineering, Denmark, with expertise within technologies for precision weeding, robot technology for agricultural purposes, and machinery management.

The additional partners in the project are Vitus Bering, Denmark, with competences within hydraulics, electrical control, and software development; Special Maskiner, Denmark, with many years experience within specialized machinery to nurse green areas; Eco-Dan a/s, Denmark, which is the leading supplier of vision based solutions for automatic tool guidance within row crops; The horticultural enterprise Inge-Marienlund, Denmark, which is the largest producer in Denmark of garden lettuce, china cabbage, and organic onions, grown as a part of the approximately 170 ha farmed according to organic principles.

2.1 Hardware

The hardware design is modular and will to the largest extent be based on standard components, making tailored components the last resort.

2.2 Software

The software is based on open source and open standard principles. Further, the developer's kits for the software environments should be easy available and inexpensive to acquire.

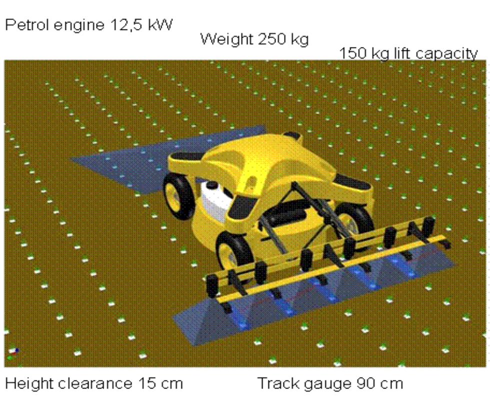
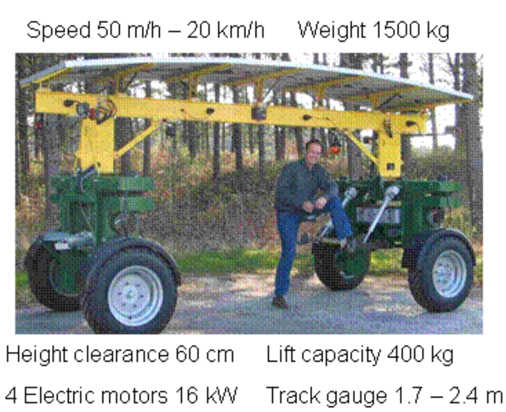
2.3 The Voice of the Customer

The overall QFD approach involves the ranking of technical specifications in relation to their degree of contribution to the fulfillment of customer or user requirements. In other words, the requirements of various interested parties are transformed into a description of the technical specifications. Akao and Mazur (2003) defined QFD as "a method for developing a design quality aimed at satisfying the consumer and then translating the consumer's demands into design targets and major quality assurance points to be used throughout the production phase". The analysis steps in this paper focus on: 1) determining customer requirements, 2) ranking the requirements, and 3) competition benchmarking. For further details see Sørensen *et al.* (2006).

2.4 Selected Competitive Tool Carrier Systems for Weed Control

The HortiBot tool carrier – see also Jørgensen et al. (2006) - was compared with possible competitive tool carriers, here the GreenTrac tool carrier (Sørensen and Frederiksen, 2002) and the tractor equipped with Auto Guidance by AutoFarm – see table 1.

Table 1. Competitive tool carrier systems

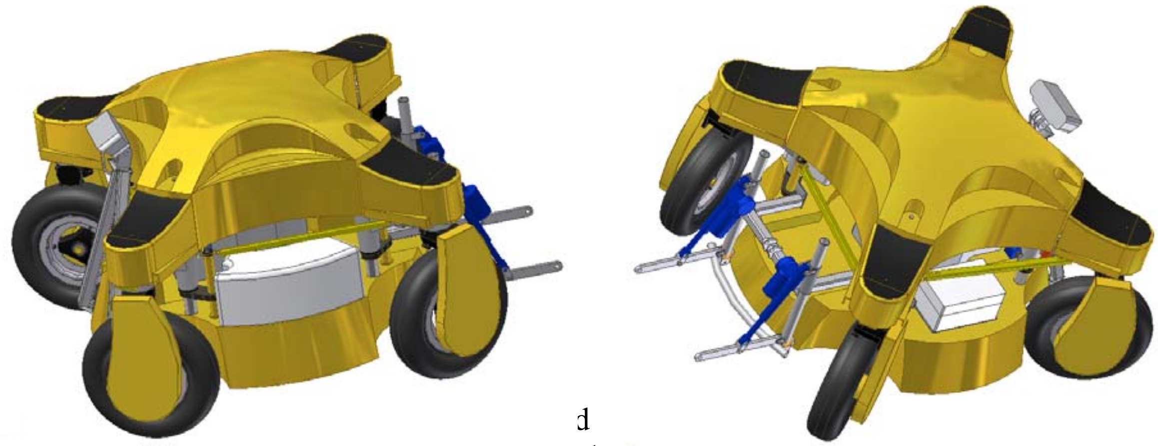
	HortiBot is a future commercial produced and robust tool carrier. It will enable an automatic execution of one-sided repetitive weeding for outdoor gardening. The HortiBot will be able to carry light weeding tools for parcels of 5–6 rows. No prior planning is needed before starting a weeding job, as the steering is primarily based on a computer-vision-based guidance system. Typically, the operator is an unskilled worker, whose primary job is to monitor one or several weeding robots instead of performing the labor-intensive work manually.
	GreenTrac is a future tool carrier to be used in the growing season with light tools such as an inter-row cultivator for row crops. Without human assistance, it operates performing light work. The

	GreenTrac navigates within the field by use of high-precision satellite navigation, requiring that the exact parcel positions and each crop row position must be known beforehand. Each job is planned at the office and then transferred to the GreenTrac's computer. For safety reasons some sort of monitoring will be necessary. However, several vehicles can easily be surveyed by the same person.
	The tractor is equipped with AutoFarm RTK AutoSteer, which enables machine control for repetitive treatments in the field with an accuracy of 3 cm. With this system, the parcels can be placed in the same locations year after year, reducing the soil compaction of the growth media. AutoFarm RTK AutoSteer is easy to learn and to use for most operators familiar with tractors. The job is planned at the office on an ordinary computer and then transferred to the tractor. A driver is required to perform turns at the headlands and to control the tools on the tractor.

3. RESULTS

The best suited platform identified as offset for a serial produced, reliable, and robust robot for horticultural weeding was found in Spider ILD01. Spider ILD01 is a slope mower for maintenance of uneven terrain with slopes up to 40° and is developed and produced by Dvořák Machine Division, Czech Republic. The propulsion of the four wheels is driven by a central hydraulic motor and the steering by a central electrical DC motor. The Spider is remotely controlled by an operator and is changing its heading by turning all 4 wheels in parallel. Hence, the orientation of the vehicle is not controllable, which will be a necessity for future operation within row crops. This transformation of the conventional Spider slope mower into a tool carrying and autonomous robot for horticulture is detailed in the following.

Visually, the changes to the original Spider ILD01 slope mower are minimal as a result of transforming it into the HortiBot as illustrated in figure 1.



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system, and lift arms.

3.1 Hardware

Overall, the main change to the Spider slope mower has been transforming the joint wheel control to individual controllable wheel modules. Each wheel module consist of a hydraulic motor for propulsion, a DC motor for steering, speed and wheel angle sensor, and a control module. The engine is also controlled by a control module, a lift arm with a control module is mounted, and a central HortiBot Control Computer (HCC) has been mounted. The communication between all units is based on a proprietary high speed CANbus. A joint control module based on a 16 bit Atmel AVR microprocessor has been developed for the 4 wheel modules, the engine control module, and the lift arm module. The overall mechanical setup and electrical interfaces of the HortiBot can be seen in figure 2.

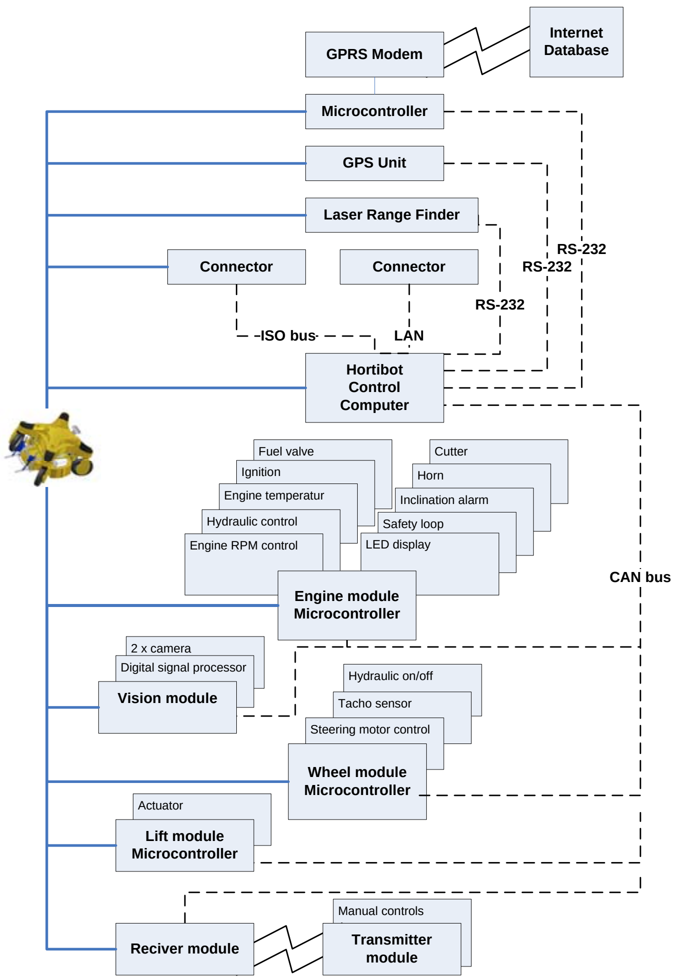

Figure 2. Hardware mechanical-electrical interfaces. The full lines indicate hardware units mounted on the HortiBot. The punctuated lines indicate electrical connections for communication.

The HCC is responsible for performing the HortiBot basic tasks such as position estimation, path following control, payload handling, emergency response, etc. The HCC is an embedded computer based on the industrial standard PC/104 architecture.

The vision module from Eco-Dan A/S, Denmark, is a new stereo vision system which captures color and 3D information from horticultural and agricultural scenes. The output from the latter system is expected to be adequate for the HortiBot navigating within transplanted onion parcels.

The standard transmitter or manual control unit for the Spider ILD01 slope mower is used as remote control for the HortiBot. However, the Spider receiver unit, which also functions as the Spider main control units, has been exchanged with a tailored CANbus enabled receiver, Receiver-R-CAN NANO-$L_{/A2}$, from NBB Germany.

3.2 Software

The main software solutions with concern to the HCC and the AVR based function modules will briefly be presented in the following.

3.2.1 HortiBot Control Computer

The operating system of the HCC is an embedded Linux distribution, iComLinux developed by Cetus, Denmark (www.cetus.dk). The iComLinux mounts the Compact Flash card read-only, and during normal operations all writing operations are performed on a RAM-disk. This has the advantage that the HCC can be switched off at any time without causing file system errors.

The HCC is connected to the sensors, actuators and communication interfaces via external modules interfacing to the HCC via a Controller Area Network (CAN) bus or via serial ports.

The software architecture of the HCC is structured as a set of software modules interfacing to each other via a shared data structure. Each software module is compiled as a Linux program, and it uses the built in Linux shared memory and semaphore features to access the shared data structure. Hence, the software modules can be started, stopped, added and upgraded independently.

3.2.2 AVR Based Function Modules

In order to ensure a functional and stable design adaptable to future changes and functionalities, the HortiBot design has been inspired by the automobile industry, which has a long experience in creating stable and modulated designs.

This design provides the following benefits:

- Each function module handles all the detailed control of the individual functions.
- Each function module can be designed and tested independently of each other and the HCC.
- Function modules can easily be reused in future applications. It is easy to make special versions of modules to meet specific needs.
- It is possible to select the best computer/controller hardware in each module to obtain the specific functions of the module.
- The total functionality of the HortiBot can be extended without being limited by the capacity of the HCC.
- The benefit of a structured modularized design includes, that the demand for special hardware for the HCC is dramatically reduced and a module can easily be changed without any influence on other modules.

The Function modules have a shared design. All function modules require the following components as a minimum (fig. 3):

- *CAN-Protocol Handler* handles the CAN-bus protocol.

- *Command Handler* is a component built to interpret the commands sent from the HCC via the CAN-Protocol Handler and control the functions in the module.
- *Module Function x* (x = 1,…,n) are components handling the specific functionality of the module and handles the interface to sensors and actuators used in the module.
- *Utility Package* is a package containing a number of general utility components. These utilities will be available in all function modules, and be based on a joint source code.

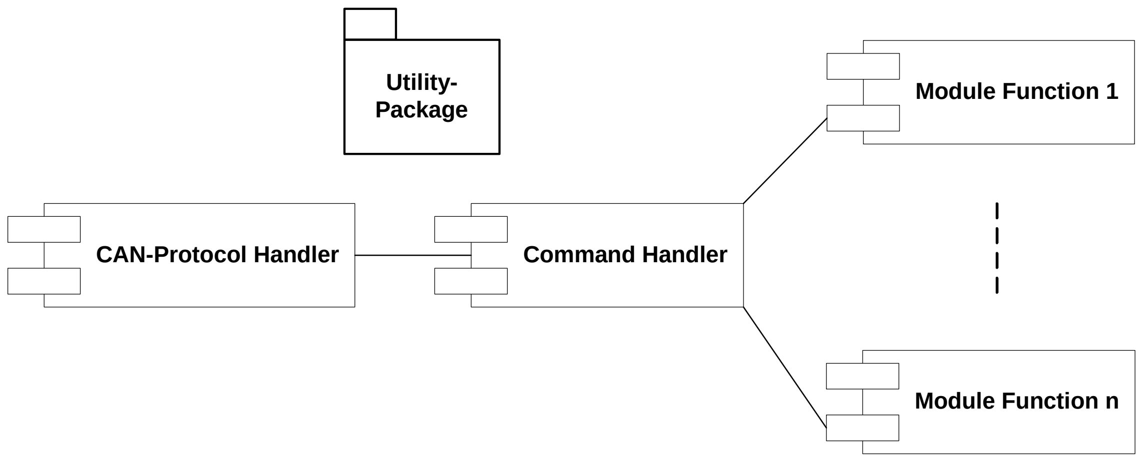

Figure 3. The components in function modules.

3.3 The Voice of the Customer

Possible customer requirements were identified using various information sources like literature review, current research activities in the robotic area, existing product screening, etc. Also, semi-structured interviews with progressive horticulturists were used to consolidate the preliminary requirement identifications. See also Sørensen *et al.* (2006).

Based on the modified importance ratings and the resulting importance ratings, the overall range of requirements were sorted in descending order in figure 4. Important user requirements include adjustability to row distance and parcel size, profitability, minimum damage to crops, and reliability. Lower ratings are attributed to requirements like affection value, prestige; attractive look, out of season operations, and use of renewable energy. The yellow full line in figure 4 represents the performance ratings of the HortiBot, the green line with punctuation represents the importance ratings of the GreenTrac, and the black dotted line with punctuation represents the tractor with AutoFarm AutoSteer. Score 0 equals to not important and score 5 equals to very important. The result is based on 35 interviews made in Denmark, Germany, and Switzerland.

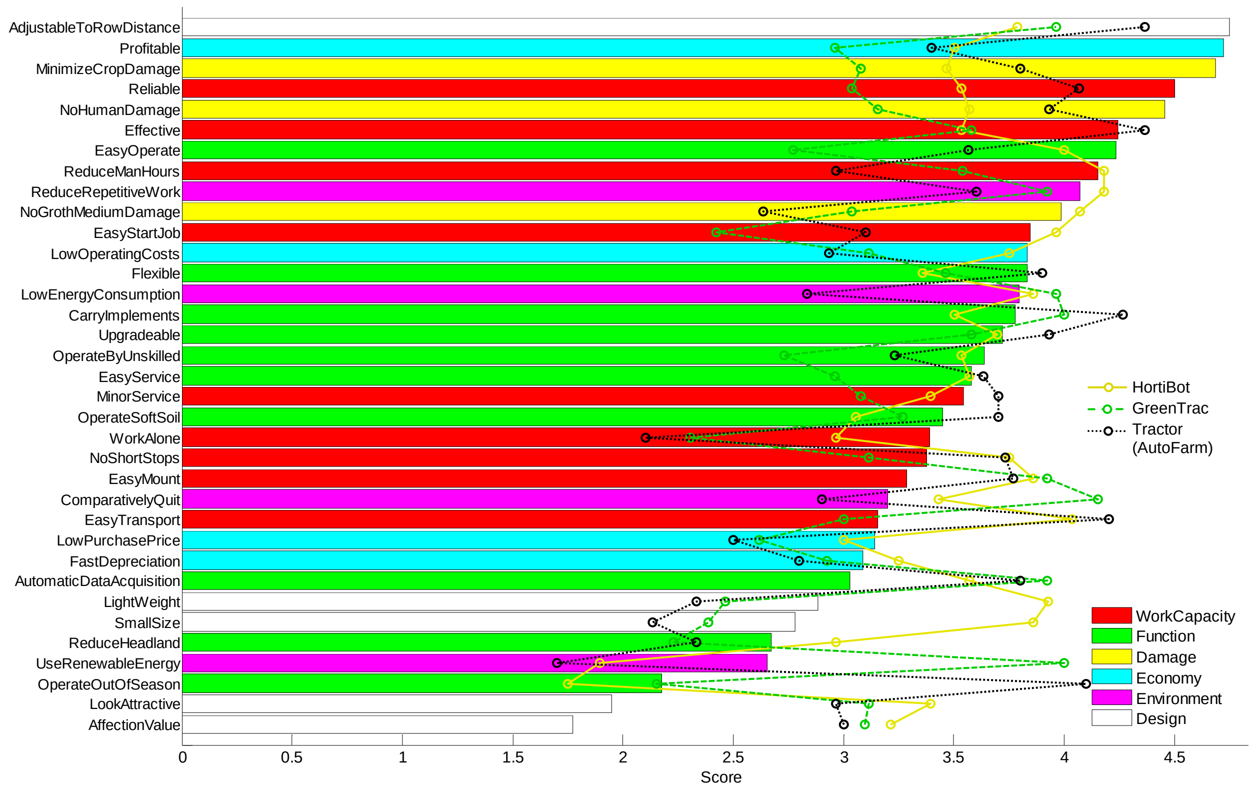

Figure 4. Average importance ratings for the overall range of requirements.

3.4 Competitive Tool Carrier Systems for Weed Control

In order to evaluate the market for Horticultural tool carriers in terms of identifying the relative position of the proposed product (HortiBot) in the market and specifically, assign priorities for further improvement, the already identified customers rated the relative performance of the three competitive products using a 5 point score scale.

The overall performance ratings of the three competing products in figure 4 show that, for example, the tractor with auto steering scores high on requirements like reliability, adjustability to field conditions, effectiveness, flexibility, etc., while the GreenTrac scores high on requirements like low energy consumption, automatic data acquisition, noiseless operation, use of renewable energy, etc. The HortiBot gets high performance ratings on requirements like reduced man-hours, minimized crop damage, profitability, reduced repetitive work, low operating costs, easy to operate, etc. It is characteristic that, for example, the GreenTrac gets relatively high performance ratings on requirements, which, on the other hand, the users deems less important.

4. DISCUSSION

By modifying a remote controlled slope mower, it has been shown that it is possible to produce a robust horticultural tool carrier. Weeding is the most profitable operation to automate within outdoor horticulture. Nørremark *et al* (2006) concluded that most promising weeding tools were laser, rotary steel rods or L-tines and mower. All these tools are relatively light in their construction. Hence, the HortiBot, which can only be able to carry relatively light implements, seems a suitable carrier.

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. The HortiBot does not fulfill these demands entirely. However, the modular design makes it relatively simple to adapt the HortiBot. Still, this will demand a redesign of the Spider ILD01 slope mower.

Due to the Open Source principles with concern to the HCC and the AVR based function modules, the HortiBot may be of value for educational institutions and universities in need for a simple and robust tool carrier.

5. CONCLUSIONS

By modifying a remote controlled slope mower it is possible to produce a robust horticultural tool carrier for outdoor horticultural weeding. Due to the open source principles used, the HortiBot may be developed further by other institutions.

QFD is a valuable tool that can be used when developing a new product. It is a structured method where customer requirements can be analyzed and built in during the design stage. In this paper, it was demonstrated how a selected part of the QFD process was carried out for a robotic tool carrier to be used in horticulture.

Based on a combination of importance ratings and competitive priority ratings important user requirements include easy adaptation to field conditions in terms of row distance and parcel size, profitability, minimum crop damage during operation, and reliability. Lesser importance was attributed to affection value, attractive look, the possibility of out of season usage, and the use of renewable energy.

The study has demonstrated the feasibility of applying a systematic planning technique for translation of the “voice of the customer” into the specific design and technical specifications of a robotic tool carrier to be used in horticulture.

Further research will comprise identifying technical specification which best match the identified customer requirements.

6. ACKNOWLEDGEMENTS

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