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Conceptual and user-centric design guidelines for a plant nursing robot

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Current service robots have relatively primitive behaviours and limited interaction with the environment. Technological foresights have indicated that the next generation of service robots will demonstrate a high degree of autonomy and reliability, have minimal impact on the environment, and will interact in a flexible way with the user. It is necessary therefore, to determine the functional requirements for a future energy-efficient robotic bioproduction system from the perspective of various stakeholders, together with the development of a high-level framework for designing and prototyping the common functionalities of mobile robots.

This study presents technical guidelines for the design of a plant nursing robot. The methodology uses Quality Function Deployment (QFD) functionalities involving the identification of relationships between identified user requirements and the derived design parameters. Extracted important user requirements included: 1) adjustable to row distance and parcel size, 2) profitable, 3) minimize damage to crops, and 4) reliable. Lower ratings were attributed to requirements such as: 1) affection value, prestige, 2) look attractive, 3) out of season operations, and 4) use of renewable energy. Subsequent important derived design parameters included: 1) PreparedForModularTools, 2) ControlableByExternalModules, 3) SemiAutonomous, and 4) Local- and GlobalPositioningSystem. The least important design parameters included: 1) OpenStandardSoftware, 2) Well-builtAppearance, 3) WheelsWithInfiniteSteeringRotation, and 4) InternalSafetySystem.

The study demonstrates the feasibility of applying a systematic design technique and procedures for translating the 'consumer's voice' into the design and technical specifications of a robotic tool carrier to be used in bioproduction.

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1. Introduction

The development of technology in agriculture and horticulture contributes significantly to the maintenance and development of efficient food production. Currently, both traditionally and organically produced products in the agri-food chain face considerable challenges in terms of economy, production efficiencies and environmental issues. These challenges are categorized under headings such as soil fertility (Kuht and Reintam, 2004), working environment (Kondo and Ting, 1998), reductions in pesticide use (Levidow and Bijman, 2002), energy consumption (Dalgaard *et al.*, 2001) and nutrient leaching (Kronvang *et al.*, 2008), among others. For example, the demands for rationalization, the prevailing shortage of labour and high wages have resulted in the use of large heavy machines in agriculture. Hence, increased operations efficiency has been achieved but, at the same time, the soil structure has been damaged and the function of the soil as a growth medium has been compromised. In the long run, this is expected to result in irreversible problems with plant growth (Hamza and Anderson, 2005). Furthermore, the combination of heavy machinery and a compacted soil increases the power requirement and energy demand for various field operations, in some cases up by to 70–80% (Jensen *et al.*, 2002).

These challenges require innovation in terms of new machinery types and increased automation at various process levels, including robot technologies. However, the progress of innovation has been impeded by various barriers including costly and insufficiently robust mechanical technology, limited operational capability and, most importantly, an inability to develop and design a technology that integrates sufficiently with the user and the dynamic working environment (Kondo and Ting, 1998; Kassler, 2001; Dario *et al.*, 2004). The development and design of innovative technologies have often lacked user acceptance when users or stakeholders have not been sufficiently involved in the design and engineering of requirements (Kujala *et al.*, 2005). Therefore, there is a great need for research and development efforts devoted to incorporating user preferences and requirements in a multidisciplinary way. Already, within specific research areas, a more user-centric approach in developing new technologies is emerging (see, e.g., Akao and Mazur, 2003; Nurkka *et al.*, 2007).

The concept being considered comprises a tool carrier for high-tech plant nursing of crops such as organically grown vegetables. High-tech tools for weeding include lasers, micro-sprayers and various mechanical devices (Nørremark *et al.*, 2006; Tillett *et al.*, 2008; Christensen *et al.*, 2009). Scenario analyses show considerable economic benefits from automating the weeding process through the implementation of a robotic tool carrier equipped with a weeding implement (Sørensen *et al.*, 2005; Pedersen *et al.*, 2007). However, the benefits are dependent on the actual design of the tool carrier and implements, and the subsequent operational performance in terms of capacity and weeding efficiency. An operationally efficient tool carrier requires that the design and technical specifications be precisely matched to the implementation conditions and to the user's requirements.

The proposed robot platform is expected to target a broad range of market segments involving integrated robot solutions and to include: small robots for horticulture, e.g. weeding robots; autonomous or remote-controlled feeding units for use within cattle or pig production; robots for the nursing of trees, e.g. weeding in various kinds of plantations; and autonomous or remote auxiliary vehicles for use within the construction business. Sørensen *et al.* (2008) have estimated that the potential market size may be as much as 900 000 robotic platforms, including those for both organic and non-organic livestock production. However, if the likelihood of a slow adoption of the technology is considered, the actual potential market size may be reduced to 250 000.

Within the concept of Total Quality Management (TQM), a number of tools have been adapted to assist in the process of customer-driven planning and engineering for product development (Cohen, 1995). One such tool is Quality Function Deployment (QFD), which has as its primary goal the translation of customer requirements into technical requirements at each stage of product design and production (Crowe and Cheng, 1996; Chan and Wu, 2005). The process involves identifying customers' requirements for a product (the 'what's), customers' views 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 customers' requirements into measurable engineering requirements or design parameters (the 'hows's) through careful evaluations performed by technicians recognizing the relationships between customer requirements and engineering characteristics.

QFD has been successfully applied in developing new products as well as in improving existing products in a range of industries and businesses, from aerospace, manufacturing, software, communication, information technology (IT), transportation, government, to service industries (see, e.g. Mrad, 1997; Chen *et al.*, 2004; Bhattacharya *et al.*, 2005; Haghiac and Haque, 2005; Miller *et al.*, 2005; Zheng and Chin, 2005; Lang, 2006). Over the years, QFD has evolved and has been modified to accommodate new demands from the users of this method in terms of, for example, time-constrained product development processes (Akao and Mazur, 2003).

The aim of this paper is, first, to identify user requirements, by extraction from users through a systematic process, for the design of a robotic tool carrier to be used for carrying various implements for plant nursing and, second, to derive design parameters satisfying user preferences, and supporting durable engineering solutions. The process includes initial steps of the QFD method framing the design process.

2. Materials and methods

In order to facilitate the user requirement analysis, a baseline prototype vehicle was chosen to frame the design process. The focus is on a semi-autonomous tool carrier unit for weeding operations carrying relatively light implements. The prototype of the plant nursing robot, HortiBot, was used to indicate the possible scope of the design process in terms of

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application issues, design constraints, etc. but still retain the user requirements analysis to be targeting a plant nursing robot in general. The HortiBot is a small automatic tool carrier (see www.HortiBot.com) based on an existing commercial machine (Jørgensen *et al.*, 2006), which was nominated as best robotic invention of the year (Summers, 2007). The HortiBot is able to carry out light weeding tools for parcels of 5–6 rows (see Fig. 1).

2.1. The QFD process

The overall QFD approach involves the ranking of technical specifications in relation to their degree of contribution to the fulfilment of customer or user requirements. In other words, the requirements of various interested parties are transformed into a description of the technical design parameters. The specifics of the QFD process have been described by a number of authors (e.g. Akao, 1990; Chan and Wu, 2005) and include the following steps:

2.1.1. Step 1: Customer identification

The first step involves identifying the customers in terms of operators, managers, etc. of the proposed product. The number of customers to interview is important in the process of balancing the costs of interviewing and analysis and the benefits of identifying more completely the requirements and their importance. Griffin and Hauser (1993) showed that in order to identify 90–95% of customer requirements, 20–30 interviews are sufficient in many cases.

2.1.2. Step 2: Customer requirements

The goal in step 2 is to develop a list of customer requirements that might affect the design and operational performance of the proposed product and stating the prerequisites, like the presence of human surveillance. Normally, the number of identified customer requirements is numerous and there is a need to group these requirements into main categories each containing a number of sub-requirements.

2.1.3. Step 3: Prioritizing customer requirements

An important step in the QFD process is the assignment of relative importance (as perceived by the customer) to each requirement. In this way, a weighting factor is generated for each requirement and this factor will give the product designer an idea of how much effort, time and money to devote to the specifics of each individual requirement. An often used measure is a 5-point scale defined as follows: 1 = not at all important, 2 = not very important, 3 = fairly important, 4 = very important, and 5 = extremely important.

The determination of the relative importance ratings includes averaging customer perceptions of the identified requirement. Suppose that, by conferring with advisors and other experts in the area of outdoor horticulture, c number of customers or users, denoted as $U_1,\ldots,U_c$, are selected and R requirements are identified and denoted by $X_1,\ldots,X_R$. Suppose that, for customer requirement, X_r, customer U_c provides an importance rating i_{rc} to it according to the scale described above, then the resulting average relative importance rating i_r for X_r is estimated by

$$i_r = \sum_{c=1}^{U_c} i_{rc}/U_c,\ r = 1, 2, \ldots.., R \qquad (1)$$

The analysis of preliminary interviews with users has shown a tendency to assign multiple same-order scores to individual user requirements, thereby masking the difference between scores. In an attempt to reveal these differences and force a prioritised ranking, arbitrary penalty weights were applied to same-order scores based on a secondary forced ranking of the same scores by the users. The maximum penalty weight is set to 0.75 indicating that a score of, for example, 5 might be regulated down to 4.25 as the next modified score would be 4.0, which is a score the user would have the possibility to apply. The penalty weights amounted to 0.25 for two equal scores, 0.50 for three equal scores, and 0.75 for four equal scores within each level of scores according to the defined scale. Table 1 shows an example of the estimation of the relative importance ratings ranging from the raw ratings to the adjusted ratings.

2.1.4. Step 4: Identification of design parameters

A workshop was arranged with participants in order to identify design parameters. The participants represented a broad range of technical expertise (see Table 2 for a list of the participants). The first part of the workshop was used to

Fig. 1 – The small plant nursing robot, HortiBot, with two different weeding tools: a herbicide cell sprayer and a tyne weeder. The system was presented at the annual Field Robot Event 2007 in Wageningen in the Netherlands.

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Table 1 – Example of relative importance ratings based on customer assessments

	Initial importance ratings				Modified importance ratings[a]				Resulting average importance ratings
Requirement (X_r)	U_1[b] i_{r1}[c]	U_2 i_{r2}	U_3 i_{r3}	$\ldots U_{35}$ $\ldots i_{r35}$	U_1 i_{r1}	U_2 i_{r2}	U_3 i_{r3}	$\ldots U_c$ $\ldots i_{rc}$	i_r[d]
X_1	5	5	4	5	5	5	4	5	4.20
X_2	5	2	1	3	4.75	2	1	3	3.40
X_3	5	5	4	5	4.50	4.75	3.75	4.75	4.20
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
X_{35}	3	4	3	3	3	4	3	3	2.80

[a] Modified importance ratings are derived by applying arbitrary weights on multiple same-order ratings. The selected weights were 0.25, 0.50 and 0.75, corresponding to 1, 2 and 3 equal scores.
[b] Customer 1 in the total of n interviewed customers.
[c] Ratings for customer 1, totalling 1225 individual ratings for all n customers and 35 requirements.
[d] Average importance ratings are estimated according to Eq. (1).

explore all the possible design parameters which could contribute to the fulfilment of the ranked user requirements. Subsequently, these design parameters were subdivided into six principal categories and the total number of design parameters was limited as much as possible.

2.1.5. *Step 5: Determination of relationships*

The degrees of relationship between the user requirements and the identified design parameters were determined by the 11 experts listed in Table 2. First, a common understanding of the task of ranking the relationships was established. Next, each relationship was elaborated in terms of technical characteristics, costs involved, etc. and ranked according to consensus.

2.1.6. *Step 6: Correlation between the design parameters*

The degrees of correlation between the design parameters were assessed by the 11 experts listed in Table 2. The measure of correlation (as used in Table 5) was ● = strong positive, ⊙ = weak positive, blank = no correlation, ○ = weak negative, and △ = strong negative. Mainly positive correlations indicate that the vehicle will be easy to construct because all design parameters are pulling in the same direction. However, mainly negative correlations indicate that a solution needs to combine conflicting design parameters in a single vehicle. If this is the case, a suggested solution in some cases would be to split the project and design two separate vehicles specialized for the two divergent customer groups.

The relative scores estimated for each of the design parameters were then sorted. Intervals of the relative scores were determined based on identifiable and distinct scoring groupings of the design parameters using hierarchical clustering (Mardia *et al.*, 1979) in MatLab (MathWorks Inc.). Cluster analysis was used to derive and assign each of the design parameters into k different groups of importance rankings (IRank): $k = \sqrt{n/2}$, where n is the total number of design parameters (Mardia *et al.*, 1979).

The QFD XL software package from SigmaZone (see www.sigmazone.com), which integrates into Microsoft Office Excel 2007, and the QFD sheet were used to enter the relationships and to estimate the relative importance score for each of the identified design parameters. Matlab R2007b (MathWorks Inc.) was used for the sorting and graphical presentation of the design parameters according to the relative scores.

3. Results

3.1. *Customer identification*

Progressive horticulturists in Denmark, Germany and Switzerland were identified by consulting advisors and other experts in the area of outdoor horticulture. The largest category of respondents was managers and/or owners. In this study, 35 customers were contacted and provided their assessment of the identified requirements. The respondents comprised 24 from Denmark, 3 from Germany, and 8 from Switzerland; 14 organic growers with an average cultivation area of 34 ha and 14 conventional growers with an average acreage of 67 ha were included, together with 7 plant nurseries in Denmark each covering 96 ha on average.

3.2. *Identification of customer requirements*

Possible customer requirements were identified using various information sources such as literature reviews, current research activities in the area of robotics, existing product screening, etc. In addition, semi-structured interviews with progressive horticulturists were used to consolidate the preliminary requirement identifications.

Six generic requirement categories were identified for the future tool carrier for weeding in outdoor horticulture (see Table 3).

Based on the modified importance ratings and the resulting importance ratings for X_r listed in Table 1, the overall range of requirements was sorted in descending order, as shown in Fig. 2.

Important user requirements included X_{31} (adjustable to row distance and parcel size), X_{23} (profitable), X_{22} (minimize damage to crops) and X_9 (reliable). Lower ratings were attributed to requirements such as X_{33} (affection value, prestige), X_{32} (look attractive), X_{18} (out of season operations) and X_{30} (use of renewable energy).

3.3. *Selected design parameters*

The 31 design parameters identified by the workshop participants are shown in Table 4. The arrow next to each design parameter indicates whether the contribution of the

Table 2 – Workshop participants, affiliations, and core competences used to identify design parameters and to determine relations between user requirements and technical characteristics

Participant and affiliation	Core competences
Rasmus N. Jørgensen, University of Southern Denmark	Bioproduction systems; plant nursing robotics; QFD
Claus G. Sørensen, University of Aarhus	Bioproduction systems; system analysis; QFD
Jørgen Maagaard, University of Southern Denmark	Mechanical design; system design, prototyping; QFD
Svend Erik Thomsen, Sauer–Danfoss	System design, agricultural applications
Thomas Langvad Jensen, DesignPartners	Industrial design; user-centred design; product optimizing
Keld K. Bertelsen, Robocluster & Designskolen Kolding	Field robot design; integration of ethics; aesthetics and social awareness; user-centred design; cross-disciplinary approach; visualization
Peter Lykkegaard, Danish Technological Institute	Safety and hazard analysis; autonomous robotics vs. end users and third parties
Finn T. Thomsen, Danish Technological Institute	System integration; robot programming; Computer Aided Design/Computer Aided Manufacturing (CAD/CAM) system development
Lars Dalgaard, Danish Technological Institute	Design and realization of autonomous robotic systems
Anne-Mette Kenley, DesignPartners	Industrial design; user-centred design; product optimizing
Iraj Biabani Nikjou, Danish Technological Institute	System development; distributed real-time system; real-time embedded systems; Unified Modelling Language (UML)

parameter to the quality of the HortiBot baseline design is positive or negative.

3.4. *Relationship rankings*

There were more than two positive relationships for each user requirement, as shown in Table 5, except in five cases: ReduceHeadland, ComparativelyQuiet, ReduceRepetitive-Work, UseRenewableEnergy and SmallSize.. This could indicate that these parameters may not be covered by the identified design parameters. Summing the raw relationships for each user requirement, the three highest values obtained were 57, 53, 50 and 50 for Profitable, Effective, Flexible and NoHumanDamage, respectively. The three lowest values obtained were 2, 4 and 5 for SmallSize,, ReduceHeadland and LightWeight, respectively.

The design parameter obtaining the highest importance ranking (IRank), as shown in Fig. 3, was focused on the plant nursing robot being prepared for modular tools PreparedForModularTools. The fact that the robot must to a certain degree be autonomous is indicated by SemiAutonomous obtaining the second best relative score, although this was closely connected to local positioning system. Local and global positioning systems (GPS) are also essential for fulfilling various user requirements. However, the local positioning (LocalPositioningSystem) is more important than the global positioning (GlobalNavigationSatelliteSystem). Finally, the user requirements regarding the tools should have the option to control or guide the robot like an implement or an additional control computer adjusting the target speed according to its ability to perform the task at hand (ControllableByExternalModules), closely connected to all entities performing physical actions and which are driven by

Table 3 – Customer requirements divided into six main categories

Main categories	Requirements, X_r,[a] $r = 1,\ldots,35$
1 Work capacity	(1) Effective (X_1), (2) works without any form of supervision (X_2), (3) reduces the number of man-hours (X_3), (4) easy to mount an implement (X_4), (5) easy to transport (X_5), (6) only minor servicing (X_6), (7) easy to start a job (X_7), (8) operates without short stops (X_8), (9) reliable (X_9)
2 Function	(1) Easy to operate (X_{10}), (2) easy to service (X_{11}), (3) upgradeable (X_{12}), (4) flexible (X_{13}), (5) carries implements for light tillage (X_{14}), (6) operated by unskilled employees (X_{15}), (7) operates on soft soil (X_{16}), (8) automatic acquisition of data (X_{17}), (9) out of season operations (X_{18}), (10) reduces the need for auxiliary areas (X_{19})
3 Damage	(1) Avoids damage to humans, animals, obstacles, etc. (X_{20}), (2) minimizes damage to growth medium (X_{21}), (3) minimizes damage to crops (X_{22})
4 Economy	(1) Profitable (X_{23}), (2) low purchase price (X_{24}), (3) low operating costs (X_{25}), (4) fast depreciation (X_{26})
5 Environment	(1) Low energy consumption (X_{27}), (2) comparatively quiet (X_{28}), (3) reduces one-sided repetitive work (X_{29}), (4) uses renewable energy (X_{30})
6 Design	(1) Adjustable to row distance and parcel size (X_{31}), (2) look attractive (X_{32}), (3) affection value, prestige (X_{33}), (4) light weight (X_{34}), (5) small size (X_{35})

[a] 35 requirements are identified and denoted by $X_1,\ldots,X_{35}$.

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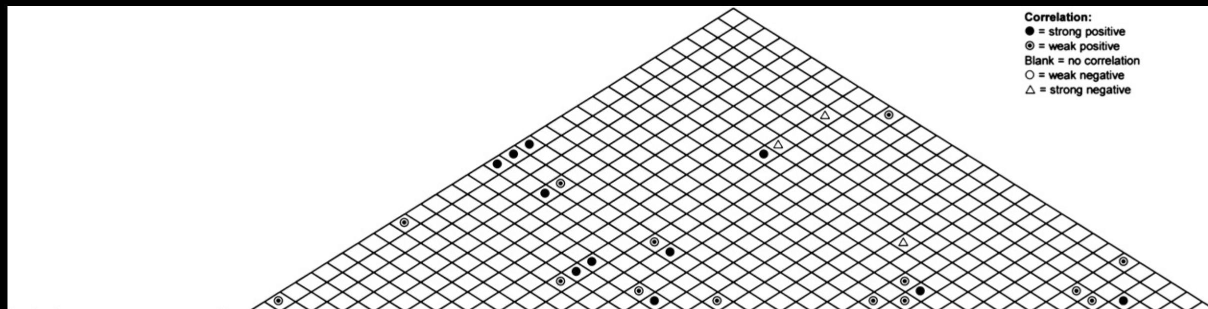
Table 4 – Selected design parameters together with intended direction of improvement and explanation and grouped within the six main categories

	Design parameter	±	Explanation
1 Work capacity	semi-autonomous	↑	Almost autonomous, requiring only minor parameterization to operate efficiently. Needs human safety surveillance and assistance a limited number of times per mission
	ControlableByExternalModules	↑	External modules such as an implement or an additional control computer can control the plant nursing robot (e.g. Pesonen *et al.*, 2007)
	OptionalOperatingCrew-Module	↑	Possible to mount an operator seat or cab for special purposes where constant control is a necessity
	OperateUnderNoLight-Conditions	↑	Can fulfil the plant nursing mission without daylight
	UserConfigurable	↑	An unskilled operator can perform simple adjustments like the changing of the wheel gauge and adjust the maximum target operating speed
	TransportGear	↑	When moving between fields, an additional high speed gear can be initiated
	ActiveStabilization	↑	Improves the manoeuvrability and stability of the vehicle and facilitates its operation in a bumpy field
	SkilledLaborConfigurable	↑	Skilled manager can perform adjustments such as changing the default parameters within the vehicle control computer
	OverallSize	↑	Increasing the size of the plant nursing robot will increase the production capacity and lower the overall sensor expenses
2 Function	RemoteControl	↑	The robot is controlled by means that does not restrict its motion with a remote control external to the device. This is often a radio-controlled device
	PreparedForModularTools	↑	Additional sensors and control systems can be added to the robot, extending its capabilities
	AdjustableLength	↑	The length of the overall vehicle can be adjusted, e.g. to create more space for an implement between the wheel pairs
	AdjustableWidth	↑	The wheel gauge can be altered, enabling the wheels to tread between the plant rows
	GroundClearance	↑	High ground clearance prevents the robot from touching and harming a standing crop when passing over it
	GlobalNavigation-SatelliteSystem	↑	Entity such as a GPS providing the current position in world coordinates with centimetre-level accuracy
	LocalPositioningSystem	↑	Entity such as a vision system giving the current position relative to e.g. plant rows
	OpenStandardSoftware	↑	'Open-standard' software is more than just a specification. The principles behind the standard, and the practice of offering and operating the standard are also described, enabling third parties to develop additional solutions. It counts for both add-on equipment and the robot software itself
	WheelsWithInfinite-SteeringRotation	↑	The wheels can change their heading orientation without limitations from e.g. wires. This will reduce the navigational limitations
3 Damage	WheelDimension_PressureArea	↓	By increasing the wheel radius or wheel width, the soil compaction will be reduced
	SupervisionIs-Prerequisite	↑	In addition to the non-skilled operator in the field, a skilled person must continuously and actively supervise the vehicle during the current mission
	RemoteSurveillance	↑	Besides the non-skilled operator in the field, an additional remote safety system surveys the behaviour of the operating plant nursing robot
	InternalSafetySystem	↑	Safety system preventing hazardous robot behaviours caused by internal errors from e.g. software
4 Economy	ExternalSafetySystem	↑	Safety system preventing the robot from e.g. collisions with obstacles such as humans, trees, or ditches
	EasyToService_PeriodicalIntervals	↑	The periodical service, e.g. every 100 h, at the workshop is fast and easy
	MaintenanceFree_NoDailyService	↑	No service is necessary on daily basis (e.g. greasing and tightening belts)
	UseMassProducedImplements	↑	Traditionally mass-produced implements can be mounted and used by the plant nursing robot
	UseMassProducedParts	↑	The robot is mainly assembled from mass-produced parts
5 Environment	Eco-efficient	↑	Progressively reduced ecological impacts and resource intensity throughout the life cycle
	ElectricDriven	↑	All entities performing physical actions are driven by electricity
	OverallSize	↓	Increasing the size of the plant nursing robot will increase the soil compaction
6 Design	Well-buildAppearance	↑	The visual impression when looking at the plant nursing robot is robustness, streamlined, and well proportioned
	3PointLinkage-Forward&Reverse	↑	The three-point linkage/hitch can operate with a mounted implement in contact with the soil moving both forwards and backwards relative to the linkage. The linkage provides a functionality internal to the robot platform

Table 5 – Scored relationships between user requirements and the selected design parameters; the mean importance ranking of the user requirements is also given, which is used to derive the importance ranking for the selected design parameters



Importance ratings:
1 = low importance
3 = moderate importance
5 = high importance

Relationships:
9 = strong
3 = moderate
1 = weak
0 or Blank = no relationship

			Design Parametres																														
			Work Capacity									Function									Damage					Economy				Envirm.		Design	
User Requirements		Importance Rating	SemiAutonomous	ControlableByExternalModules	OptionalOperatingCrewModule	OperateUnderNoLightConditions	UserConfigurable	TransportGear	ActiveStabilization	SkilledLaborConfigurable	OverallSize	RemoteControl	PreparedForModularTools	AdjustableLength	AdjustableWidth	GroundClearance	GlobalNavigationSatelliteSystem	LocalPositioningSystem	OpenStandardSoftware	WheelsWithInfiniteSteeringRotatio	WheelDimension_PressureArea	SupervisionIsPrerequisite	RemoteSurveillance	InternalSafetySystem	ExternalSafetySystem	EasyToService_PeriodicalInterval	MaintenanceFree_NoDailyService	UseMassProducedImplements	UseMassProducedParts	Eco-efficient	ElectricDriven	Well-buildAppearance	3PointLinkageForward&Reverse
Work Capacity	Effective	4.2	9	3		9	1	1	1	3	1	1	1	1	1		3	9		1	1		3			1	1				1		1
	WorkAlone	3.4	9	1		3											3	9							1								
	ReduceManHours	4.2	9								1						3	3					3		1		1						
	EasyMount	3.3					1						9	3		3				3													3
	EasyTransport	3.2						9				3		3	3	1	1			1					1								
	MinorService	3.5									3					1								1			3		1		3		1
	EasyStartJob	3.8	3				1	1		1		1	9				1	3															
	NoShortStops	3.4	1				1			1							3	3															
	Reliable	4.5			3				1	1			3		1		1	1	1		1	3	3	3	3		3	3	3		3		3
Function	EasyOperate	4.2										3	9				1	3		1	1				1			1					1
	EasyService	3.6											3			1			3					1		9	9	3	1		3		1
	Upgradeable	3.7		3									9	1	1		3														1		
	Flexible	3.8		9	9	1	3	1	1	3		1	3	3	1	3	3	3	1	1											1		3
	CarryImplements	3.8							1		1		9	3		3					1							1					9
	OperateByUnskilled	3.6	1							3		3	1					3									3	1					1
	OperateSoftSoil	3.4										1				1					9										1		
	AutomaticDataAcquisition	3.0											9				3	3										1					
	OperateOutOfSeason	2.2		3	1					1			3				3	1															
	ReduceHeadland	2.7												1						3													
Dam.	NoHumanDamage	4.5		9								3	1			1	3	3				9	9	3	9								
	NoGrowthMediumDamage	4.0											1		3			1			9												
	MinimizeCropDamage	4.7	9	9					1				1		3	9	1	3		1	1	3	3	1									
Econ.	Profitable	4.7	3	1		9		1		3	9	1	3	3	1	1	3	3	1		1	1	1	1		1	1	3	3	1	1		1
	LowPurchasePrice	3.1		1						1	3								1			1						3	3		1		1
	LowOperatingCosts	3.8									3															1	1	1		1	1		1
	FastDepreciation	3.1				1					3																	1	1				
Envirm.	LowEnergyConsumption	3.8							1								1	1		1	3						1			9	9		
	ComparativelyQuit	3.2																												3	9		
	ReduceRepetitiveWork	4.1	9																														
	UseRenewableEnergy	2.7																												9	3		
Design	AdjustableToRowDistance	4.8					9								9																	1	
	LookAttractive	1.9										3																			1	9	
	AffectionValue	1.8	1	1	1																				1							9	1
	LightWeight	2.9										1																			3	1	
	SmallSize	2.8										1																			1		
	Raw score		219	160	51.9	97.8	69	45	24.8	66.3	95.5	78.1	275	66.9	99.2	97.7	136	203	26.9	41.8	104	75.5	97.6	43.4	70.3	45	88	69.4	47.3	76.2	146	41.1	102
	Relative %		8%	6%	2%	3%	2%	2%	1%	2%	3%	3%	10%	2%	3%	3%	5%	7%	1%	1%	4%	3%	3%	2%	2%	2%	3%	2%	2%	3%	5%	1%	4%
	Importance Rank		5	4	1	3	2	1	1	2	3	2	5	2	3	3	4	5	1	1	3	2	3	1	2	1	3	2	1	2	4	1	3

electricity (ElectricalDriven). The remaining design parameters have equal importance.

Some of the design parameters obtaining the lowest importance ranking, $IRank_1$, were: OpenStandardSoftware, which enables third-party companies to develop add-ons; Well-buildAppearance, which has to do with the first impressions a potential customer has; WheelsWithInfiniteSteeringRotation, which will reduce the navigational limitations and gives the robot at least six different steering capabilities including front, rear, double Ackermann, parallel, Dog Walk (preventing any wheel from following the same path in the crop), and centre turn; and InternalSafetySystem, preventing hazardous behaviours due to internal system malfunctions.

3.5. *Design parameter correlations*

Three design parameters showed negative correlations. Steering wheels with infinite rotation are not maintenance free due to its technical complexity and therefore the parameter WheelsWithInfiniteSteeringRotation conflicts with MaintenanceFree_NoDailyService. Size of the plant nursing vehicle (OverallSize) conflicts with use of mass-produced implements (UseMassProducedImplements), and electric drive (ElectricDriven) limits the size of plant nursing vehicles. The remaining design parameters had either positive correlations or none.

4. Discussion

Thirty-one design parameters were identified as having the potential to fulfil one, or preferably several, of the user requirements. This seems a rather high number but it was not possible to reduce it further while still maintaining the consensus between experts. Assuming irrelevant or redundant design parameters, the QFD matrix should show unfilled columns (Verma *et al.*, 1998). However, all design parameters have more than three relationships with the customer requirements listed in Table 5.

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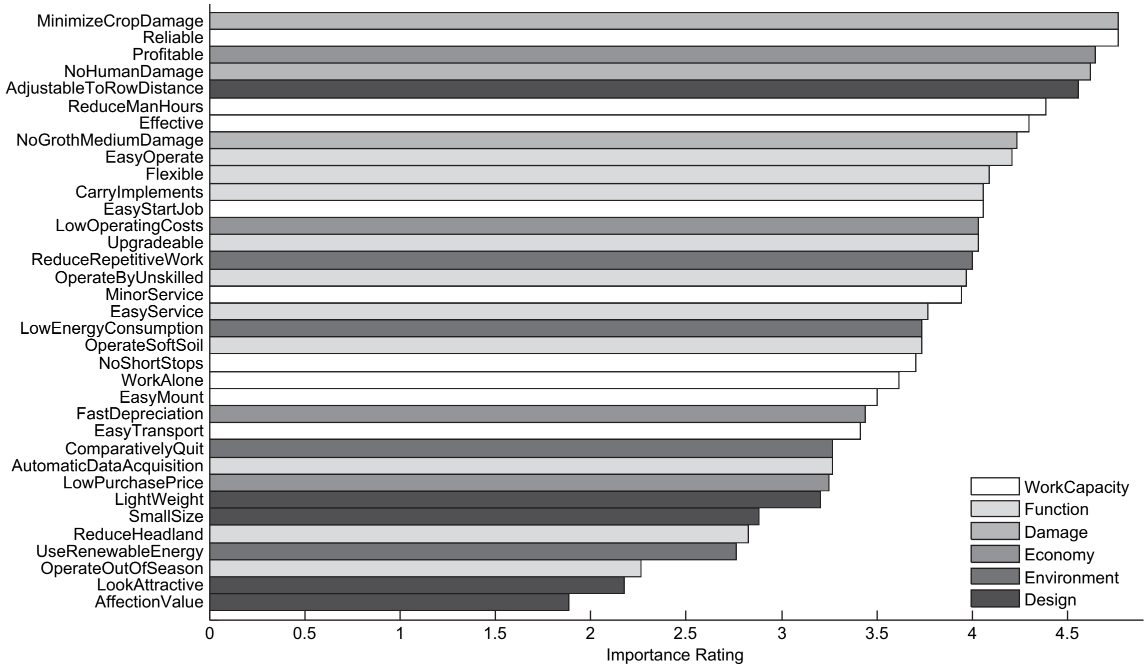

Fig. 2 – Average importance ratings for the R requirements shown in the horizontal bars. The shading of the bars indicates the six main categories: □ Work capacity; ■ Function; ■ Damage, ■ Economy, ■ Environment, and ■ Design.

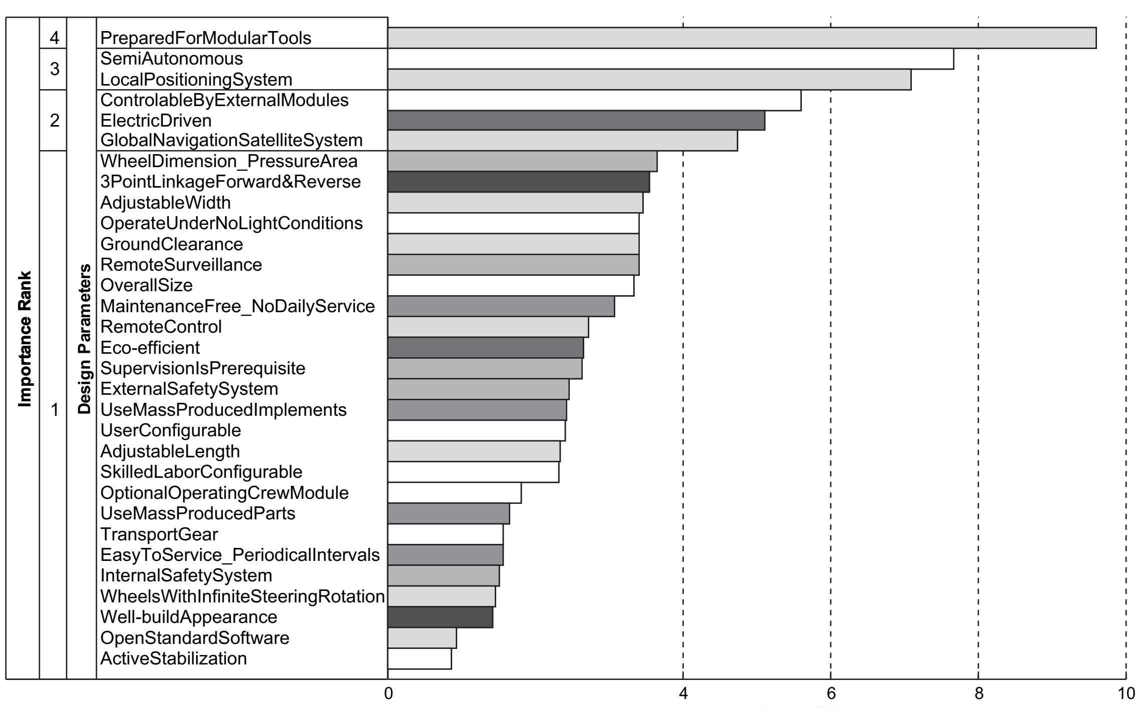

Fig. 3 – Design parameters ordered according to the relative scores obtained in Table 5. The intervals for the relative scores were set arbitrarily to derive the importance rankings 1–5 and are indicated by the vertical dashed lines and also marked in the left part of the figure. The shading of the bars indicates the six main categories: □ Work capacity; ■ Function; ■ Damage, ■ Economy, ■ Environment, and ■ Design.

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Fig. 4 – Examples of two conceptual designs of a future plant nursing robot. Left: the engineering approach HortiBot II by Petersen *et al.* (2006). Right: the industrial design approach Roboss by Sørensen, 2006.

In terms of the identified and selected design parameters, it became evident that individual design parameters did not necessarily end up at the same level of specification (as illustrated by the parameters eco-efficiency and active stabilization). However, Fig. 3 shows no trend towards specific or non-specific parameters exclusively scoring relatively high or low in the importance ranking, which justifies the original selection of design parameters.

Establishing and quantifying the relationships between the customer requirements and the design parameters required intensive elaborations in several cases in order to obtain consensus despite the fact that a common understanding had been reached. The alternative option of providing the experts with a questionnaire to complete would have excluded fruitful discussions between the experts. Hence, the workshop interaction and consensus approach seem to have been justified.

No ignored customer requirements could be identified by an empty row in the QFD matrix in Table 5. Since customer requirements drive the subsequent design and development activities, it is important to address any inconsistencies early on in the process (Verma *et al.*, 1998). In the case of the SmallSize customer requirement, only two weak relationships with the design parameters were indicated and it might be considered as having been ignored. The customer importance rating for this requirement had the low value of 2.8 and, hence, the missing relationships may not be of any great importance.

An evaluation of the results of the design parameters ordered according to relative score reveals a perceivable logical structure to the importance rankings. By invoking the HortiBot (see Fig. 1), this prototype is seen to comply with the design parameters set for $IRank_4$ and $IRank_5$, whereas it lacks compliance with the design parameters contained in the importance ranking interval 3. Conversely, the conventional modern tractor complies with design parameters both in the importance interval 4 and 5 as well as partly in 3. Further studies are warranted, but are outside the scope of this paper.

A few design parameters obtained unexpectedly low importance ranking $IRank_1$. Well-buildAppearance obtained a strong relationship in relation to the user requirements LookAttractive and AffectionValue. However, the customers had not prioritised these two parameters (giving them importance ratings of 1.9 and 1.8, respectively). This seems to be a contradiction, since the HortiBot was voted the Robotic Invention of 2007 by Time Magazine (Summers, 2007) despite it not performing well within the $IRank_3$ design parameters. It is assumed that this is due to the design features. Fig. 4 (left-hand side) is a conceptual design fulfilling many of the user requirements described in this paper from an engineering point of view.

InternalSafetySystem obtained a low score in $IRank_1$. The probable reason for this is that the relationship elaborations took place under the inherent prerequisite that a non-skilled operator may often be in charge of one or several semi-autonomous plant nursing robots. Hence, the operator can immediately engage the emergency button in the case of abnormal behaviour from the robot and the system will in principle always be safe. In the case of assuming a fully autonomous system, the IRank may have been higher. The design parameter WheelsWithInfiniteSteeringRotation gives a high degree of flexibility with regard to navigation and steering capabilities and seems attractive from a control and engineering point of view. However, this parameter could only satisfy relevant customer requirements to a minor degree.

The arbitrary penalty system developed for this study is clearly supported by the preliminary test runs of user questioning. It showed the distorting effect of using the raw scores, where in many cases it was not possible show a prioritised ranking of the user requirements. Also, the exact quantification of the penalty, in this case a maximum penalty weight amounting to 0.25 for the second equal score, 0.50 for the third, and 0.75 for the fourth within each level of scores, is estimated to only create an average difference between the raw scores and the adjusted scores of 5%.

It is important to note that the QFD approach should be seen as a multiple step process aimed at the final detailed specifications of the product under consideration, but this has been beyond the scope of this study. By changing the aim of the individual QFD steps towards more and more detailed specifications of the design parameters and using targeted cross functional teams, the final blueprint for the product construction can be derived.

5. Conclusions

The applied QFD approach enabled the extraction and ranking of user requirements and derived design parameters for the design of a robotic tool carrier for carrying various implements for plant nursing. The method provided a systematic and intuitive procedure for extracting user requirements focussing on goal alignment. Important user requirements included: 1) adjustable to row distance and parcel size, 2) profitable, 3) minimize damage to crops, and 4) reliable. Lowest ratings were attributed to requirements such as: 1) affection value, prestige, 2) look attractive, 3) out of season operations, and 4) use of renewable energy.

Based on the identified user requirements, the important derived design parameters included: 1) PreparedForModularTools, 2) ControlableByExternalModules, 3) SemiAutonomous, and 4) Local- and GlobalPositioningSystem. The least important design parameters included: 1) OpenStandardSoftware, 2) WellbuiltApperance, 3) WheelsWithinfiniteSteeringRotation, and 4) InternalSafetySystem.

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REFERENCES

Akao Y (1990). Quality Function Deployment: Integrating Customer Requirements into Product Design. Productivity Press, Cambridge, MA.

Akao Y; Mazur G H (2003). The leading edge in QFD: past, present and future. International Journal of Quality and Reliability Management, **20**(1), 20–35.

Bhattacharya A; Sarkar B; Mukherjee S K (2005). Integrating AHP with QFD for robot selection under requirement perspective. International Journal of Production Research, **43**, 3671–3685.

Chan L K; Wu M L (2005). A systematic approach to quality function deployment with a full illustrative example. Omega, **33**, 119–139.

Chen C Y; Chen L C; Lin L (2004). Methods for processing and prioritizing customer demands in variant product design. IIE Transactions, **36**, 203–219.

Cohen L (1995). Quality Function Deployment: How to Make QFD Work for You. Addison-Wesley, Reading, MA.

Christensen S; Søgaard H T; Kudsk P; Nørremark M; Lund I; Nadimi E S; Jørgensen R (2009). Site-specific weed control technologies. Weed Research, **49**, 233–241.

Crowe T J; Cheng C C (1996). Using quality function deployment in manufacturing strategic planning. International Journal of Operations & Production Management, **16**, 35.

Dalgaard T; Halberg N; Porter J R (2001). A model for fossil energy use in Danish agriculture used to compare organic and conventional farming. Agriculture, Ecosystems & Environment, **87**(1), 51–65.

Dario P; Dillman R; Christensen H I (2004). EURON Research Roadmaps. Robotics: European Research Agenda

Griffin A; Hauser J R (1993). The voice of the customer. Marketing Science, **12**(1), 1–27.

Haghiac H A; Haque I (2005). Quality function deployment as a tool for including customer preferences in optimising vehicle dynamic behaviour. International Journal of Vehicle Design, **39**, 311–330.

Hamza M A; Anderson W K (2005). Soil compaction in cropping systems a review of the nature, causes and possible solutions. Soil and Tillage Research, **82**(2), 121–145, June 2005.

Jensen E S; Vejre H; Bügel S H; Emanuelsson J (Eds.) (2002). Visioner for fremtidens jordbrug. [Visions for future agriculture]. Center for Økologi og Miljø, Gads Forlag.

Jørgensen R N; Sørensen C G; Jensen K; Søgaard H T; Pedersen J M; Sørensen L B; Havn I; Sibbesen S; Nielsen J (2006). Hortibot: an Accessory Kit Transforming a Slope Mower into a Robotic Tool Carrier for High-Tech Plant Nursing – Part I. 2006 ASABE Annual International Meeting, Portland Convention Center, Portland, Oregon, 9–12 July 2006.

Kassler M (2001). Agricultural automation in the new millennium. Computers and Electronics in Agriculture, **30**(1–3), 237–240.

Kondo N; Ting K O (1998). Robotics for Bioproduction Systems. ASAE Publication 05-98. American Society of Agricultural Engineers.

Kronvang B; Andersen H E; Børgesen C; Dalgaard T; Larsen S E; Bøgestrand J; Blicher-Mathiasen G (2008). Effects of policy measures implemented in Denmark on nitrogen pollution of the aquatic environment. Environmental Science & Policy, **11**(2), 144–152.

Kuht J; Reintam E (2004). Soil compaction effect on soil physical properties on the content of nutrient in spring barley and spring wheat. Agronomy Research, **2**(2), 187–194.

Kujala S; Kauppinen S; Lehtola L; Kojo T (2005). The Role of User Involvement in Requirements Quality and Project Success. Proceedings of the 2005 13th IEEE International Conference on Requirements Engineering (RE'05).

Lang C L (2006). Application of quality function deployment launches to enhancing nursing home service quality. Total Quality Management & Business Excellence, **17**, 287–302.

Levidow L; Bijman J (2002). Farm inputs under pressure from the European food industry. Food Policy, **27**(1), 31–45.

Mardia K V; Kent J T; Bibby J M (1979). Multivariate Analysis. Academic Press.

Miller K; Brand C; Heathcote N; Rutter B (2005). Quality function deployment and its application to automotive door design. Proceedings of the Institution of Mechanical Engineers Part D – Journal of Automobile Engineering, **219**, 1481–1493.

Mrad F (1997). An industrial workstation characterization and selection using QFD. Quality and Reliability Engineering International, **13**(5), 261–268.

Nurkka P; Norros L; Pesonen L (2007). Improving usability of and user acceptance of ICT systems in farming. Paper presented at the EFITA/WCCA Joint Congress in IT in Agriculture, Glasgow.

Nørremark M; Sørensen C G; Jørgensen R N (2006). Hortibot: Comparison of present and future phyto-technologies for weed control – Part III. 2006 ASABE Annual International Meeting, Portland Convention Center, Portland, Oregon, 9-12 July 2006.

Manuscript ATOE 07 011 **Pesonen L; Kaivosoja J; Virolainen V; Oittinen J; Kivipelto J** (2007). Remote assisted task management for ISOBUS equipped tractor-implement combination. Agricultural Engineering International: CIGR eJournal, **IX**. July, 2007.

Pedersen S M; Fountas S; Have H; Blackmore S (2007). Agricultural robots—system analysis and economic feasibility. Precision Agriculture, **2006**(7), 295–308.
Petersen C Ø; Sørensen A S; Tchekounang C N (2006). HortiBot 2 Mekanisk Redesign. Bachelor Thesis at University College Vitus Bering Denmark (in Danish).
Sørensen C G; Madsen N A; Jacobsen B H (2005). Organic farming scenarios: operational analysis and costs of implementing innovative technologies. Biosystems Engineering, **91**(2), 127–137.
Sørensen K (2006). The robots replaces the manual weeding tool. The Engineer. No., **34**, 2006.
Sørensen C G; Jørgensen R N; Maagaard J; Bertelsen K K; Dalgaard L; Nørremark M (2008). User-centered and conceptual technical guidelines of a plant nursing robot. 2008 ASABE Annual International Meeting, Rhode Island Convention Center, Providence, Rhode Island, USA, June 29–July 2, 2008.
Summers D (2007). Weed 'em and reap: best inventions of the year. Featured in the November 12, 2007 issue of TIME Magazine: ''The HortiBot''.
Tillett N D; Hague T; Grundy A C; Dedousis A P (2008). Mechanical within-row weed control for transplanted crops using computer vision. Biosystems Engineering, **99**(2), 171–178.
Verma D; Chilakapati R; Fabrycky W J (1998). Analyzing the Quality Function Deployment (QFD) matrix: an expert system based approach to identify inconsistencies and opportunities. Journal of Engineering Design, **9**(3), 252–262.
Zheng L Y; Chin K S (2005). QFD based optimal process quality planning. International Journal of Advanced Manufacturing Technology, **26**, 831–841.

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