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Systematic design of an autonomous platform for robotic weeding

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Abstract

The systematic design of an autonomous platform for robotic weeding research in arable farming is described. The long term objective of the project is the replacement of hand weeding in organic farming by a device working autonomously at field level. The distinguishing feature of the described design procedure is the use of a structured design approach, which forces the designer to systematically review and compare alternative solution options, thus preventing the selection of solutions based on prejudice or belief. The result of the design is a versatile research vehicle with a diesel engine, hydraulic transmission, four-wheel drive and four-wheel steering. The robustness of the vehicle and the open software architecture permit the investigation of a wide spectrum of research options for intra-row weed detection and weeding actuators.

1. Introduction

Automation of agricultural machinery is seen as a means to reduce cost in current and future field operations. Some authors have proposed multipurpose mechanical frames [1], while others presented automated agricultural machinery [2–5] or smaller autonomous vehicles for specific applications [6–9].

Automation of mechanical weed control in arable farming is one example that could contribute to sustainable food production at lower cost. Weeds in agricultural production are mainly controlled by herbicides. As in organic farming the use of herbicides is prohibited, weed control is a major problem. While there is sufficient equipment available to control the weeds in between the rows (inter-row weeding), weed control within the rows (intra-row weeding) still requires a lot of manual labour. This is especially the case for crops that are slowly growing and shallowly sown like sugar beet, carrots and onions. In 1998, on average 73 h/ha sugar beet were spent on hand weeding in the Netherlands [10]. The required labour for hand weeding is expensive and often not available. Autonomous robotic weed control systems could replace this labour and could also reduce agriculture's current dependency on herbicides, improving its sustainability and reducing its environmental impact [11].

Different robotic applications have different requirements and for the same robotic application even different assessments can be made when deciding about the technology to be incorporated as has been described by different researchers [12,7,9]. While those studies provide great insight in requirements and the assessments made about the available technology to be incorporated, the method used to achieve a final solution stays unclear. This paper presents the design of an autonomous platform for weed control research using a systematic design method from mechanical engineering. In doing so, an overview is given of alternative solutions for components of the system presented in the literature, and the benefits of applying a systematic design method are explored.

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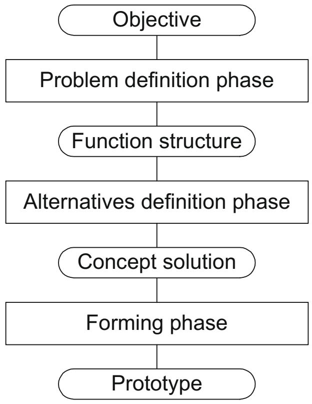

Fig. 1. The design process.

2. The design procedure

2.1. Method

The autonomous weeding robot is designed using a systematic design method described by [13]. This method belongs to a class of methods using a phase model of the product design process. These methods describe the product design as a process consisting of different phases at different levels of abstraction [14]. The phases are (1) 'problem definition phase', (2) 'alternatives definition phase' and (3) 'forming phase' (Fig. 1). The results of the respective phases are a function structure, a concept solution and a prototype, respectively.

The problem definition phase starts with defining the objective of the design. In the problem definition phase a set of requirements is established, that can be split into fixed and variable requirements. A design that does not satisfy the fixed requirements is rejected. Variable requirements have to be fulfilled to a certain extent. To what extent these requirements are fulfilled, determines the quality of the design. The variable requirements are also used as criteria for the evaluation of possible concept solutions. The last part of the problem definition phase consists of the definition of the functions of the robot. A function is an action that has to be performed by the robot to reach a specific goal. In our case, important functions are 'intra-row weeding' and 'navigate along the row'.

The functions are grouped in a function structure, which represents a solution on the first level of abstraction (Fig. 2). The function structure consists of several functions. Every function can be accomplished by several alternative principles, e.g. mechanical and thermal principles for weed removal.

In the alternatives definition phase, possible alternative principles for the various functions are presented in a morphological chart (Fig. 3). The left column lists the functions and the rows display the alternative principles. By selecting one alternative for each function and by combining these alternatives, concept solutions are established. These concept solutions are represented by lines drawn in the morphological chart. The best concept solution is selected using a rating procedure.

In the forming phase the selected concept solution is worked out into a prototype.

2.2. Application for the weeding robot

According to the ultimate research objective, formulated as 'replacement of hand weeding in organic farming by a device working autonomously at field level', the first step in the problem definition phase was to establish the set of requirements. For this purpose interviews were held with potential users, scientists and consultants related to organic farming. The resulting requirements are listed below.

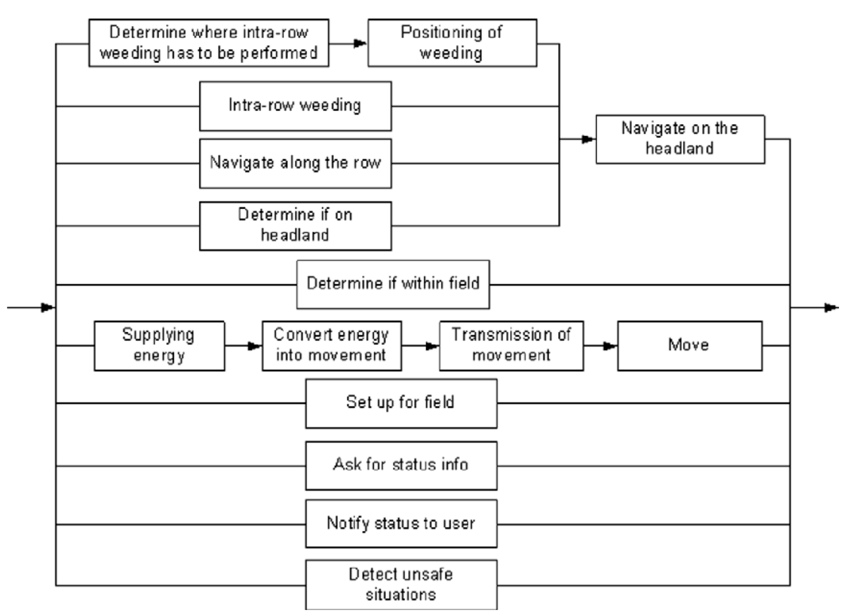

Fig. 2. The function structure.

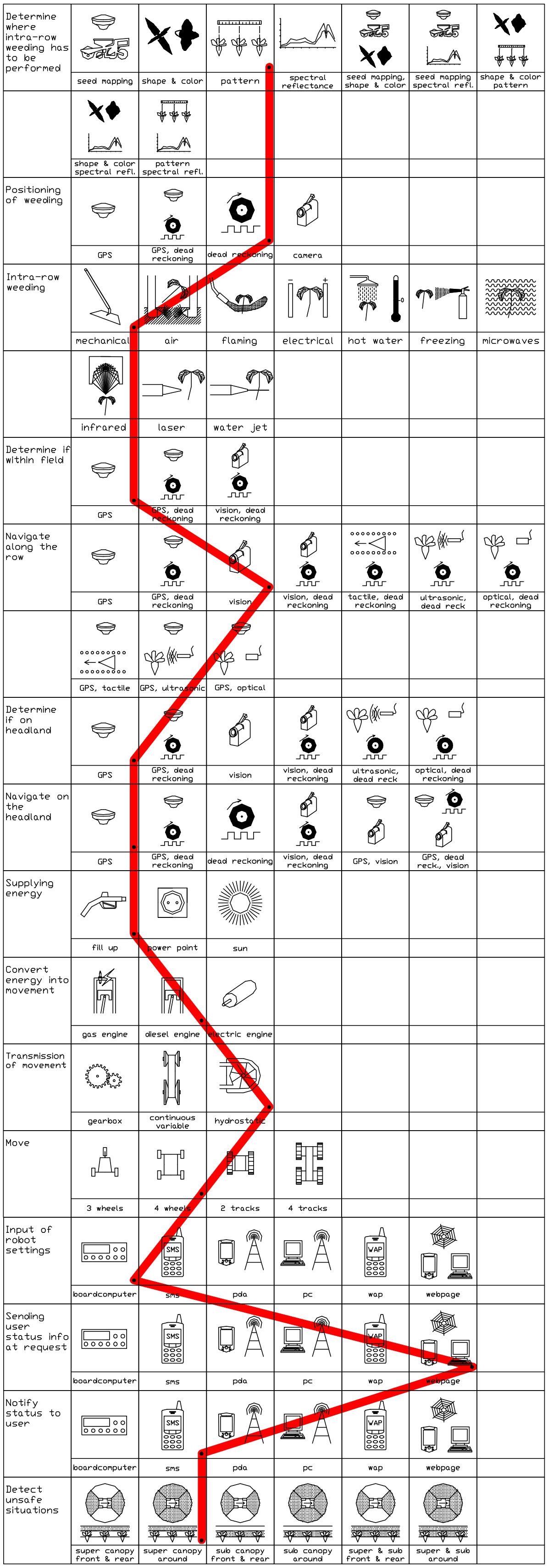

Fig. 3. Morphologic chart.

Fixed requirements:

- Replacing hand weeding in organic farming.
- Applicable in combination with other weed control measures.
- Manual control of the vehicle must be possible for moving the vehicle over short distances.
- Weeding a field autonomously.
- Ability to work both day and night.
- The weeding robot must not cross the field boundaries.
- The weeding robot must be self restarting after an emergency stop.
- The weeding robot informs the farmer when stopped definitely, e.g. due to security reasons or when the task is finished.
- The weeding robot sends its operational status to the user at request.
- The weeding robot must function properly in sugar beet.

Variable requirements:

- Removing more than 90% of the weeds in the row.
- The costs per hectare need to be comparable to the costs of hand weeding or less.
- Damage to the crop is at least as low as with hand weeding.
- Wheel pressure of the weeding robot must be not higher than for mechanical weeding.
- Energy efficiency at least as high as mechanical weeding.
- Noise emission not higher than mechanical weeding.
- Safe for people, animals and property.
- Supervision requirement at least lower than hand weeding.
- Complexity of operation not higher than mechanical weeding.
- Reliable functioning.
- Suitable as research platform.

The requirement 'Suitable as research platform' requires some explanation. There are many open questions related to autonomous vehicles in the agricultural area. Some of these are related to the behavior in obstacle avoidance, safety manoeuvres, intelligent turns at the headland, intelligent driving strategies for covering a field or in multi-vehicle environments, and freedom in positioning of implements by manoeuvring the vehicle. In order to allow the investigation of such issues, it is desirable to have a platform with more degrees of freedom, than perhaps ultimately needed. In addition, changes in construction should be easy.

After establishing the set of requirements the functions of the weeding robot were identified. These functions were grouped into a function block scheme. This scheme is represented in Fig. 2. Functions located in parallel lines can be performed simultaneously.

The navigation system consists of four functions. Firstly, the weeding robot should constantly determine whether it is located in- or outside the field borders. Secondly, if within the field borders, it should determine whether it is on a headland or not. Thirdly, in case it is not on the headlands, it should navigate along the row and perform the intra-row weeding. Fourthly, if the weeding robot arrives on the headland, it should stop the intra-row weeding and start to navigate to the next crop rows to be weeded. This sequence repeats until the whole field, except the headlands, is weeded. Weeding of the headlands is left out of consideration. An increasing number of farmers in the Netherlands do not grow sugar beet at the headlands because they think it is not cost-effective.

In the alternatives definition phase possible alternative principles for the various functions are listed in a morphological chart (Fig. 3). Four people involved in the project drew lines indicating possible concept solutions in the chart. These concept solutions were then weighed against each other in consultation based on their expert knowledge, using the variable requirements listed above. The concept solution indicated by the line in Fig. 3 is the final concept solution. Finally, in the forming phase the concept solution was worked out into a prototype.

2.3. Results of the design process

2.3.1. Determine where intra-row weeding has to be performed

The following alternatives to determine where intra-row weeding has to be performed were taken into consideration (see also Fig. 3):

- *Seed mapping.* During seeding the positions seeds can be recorded by RTK–DGPS. A seed sensor senses the seeds while they are falling from the machine into the soil. Griepentrog et al. [15] found that the mean deviation between estimated sugar beet seed position and true plant position ranged from 16–43 mm, which means that for targeting weeds close to the crop plants additional sensing would be required.
- *Shape and color.* Plant species can be identified based on characteristic shape, colour and texture features using image analysis. Gerhards and Christensen [16] report an average identification rate of 80% using image analysis when plant species were grouped into five different herbicide classes. Åstrand and Baerveldt [17] were able to classify beets with a classification rate of 98% using image analysis. Extraction of individual plants out of a scene was done manually and the colour features used may change due to differences in soils, nutrients and sunlight. Excluding colour features, the classification rate of beets classified as beets was reduced to 80%. Åstrand [18] reports also the results of a combination of using plant pattern information and the individual plant features derived from image analysis. Crop plant classification rates of 92% and 98% on a dataset are reported using a classifier trained offline. Åstrand [18] expects that variations in plant appearance within and between fields could easily reduce the performance in a real-time field application.
- *Pattern recognition of plant spacing.* Row crops like sugar beet have approximately equal intra-row distances. Therefore, crop plants can be identified based on this regularity. Bontsema et al. [19] reconstructed individual positions of crop plants in a row successfully with Fourier transform on a signal made by a low cost infrared light barrier. The quality of detection was decreasing with a decreasing distance between the crop plants, an increasing standard deviation of the distance between the crop plants, an increasing number of weeds per meter and decreasing width of the crop plants. In experiments 80–97.5% of the crop plants were detected correctly [20,21]. Åstrand and Baerveldt [22] also present two methods to detect the position of the crop plants in the row based on the planting pattern of the crop. Crop classification rates of 78–99% were achieved.
- *Spectral reflectance.* Reflectance of crop, weeds and soil differ in the visual and near infrared wavelengths, so this spectral information has potential to be used for discrimination [23]. Vrindts et al. [24] used the reflectance spectra of sugar beet and weed canopies to evaluate the possibilities of weed detection. In field experiments up to 95% of the sugar beets were classified as sugar beets and up to 84% of the weeds were classified as weeds.

None of the methods in literature reports a sugar beet recognition rate of 100% under all conditions. Finally, pattern recognition was chosen because it is expected to be sufficient and because of its further advantages: the approach is not restricted to one specific crop and only few parameters must be known in advance.

2.3.2. Positioning of weeding

The following alternatives to position the weeding actuator at the location indicated by the plant detection system were taken into consideration:

- *GPS.* The position of the actuator can be measured by mounting a GPS antenna above the actuator position. It is questionable whether the maximum position update frequency of about 10 Hz is sufficient for a precise actuator positioning.
- *Dead reckoning.* With a wheel encoder the position of the actuator relative to the crop plant location can be measured [19]. Accumulation of inaccuracies over the distance between sensors and actuators occurs but is limited if the distance between both is small.
- *Machine vision.* A machine vision system could track both the actuator position and the position at which it should become active. To do this a specially developed image processing algorithm is needed.

The choice made is to use dead reckoning. It is sufficient, and an encoder wheel would be already available because it is also needed for the pattern recognition system.

2.3.3. Intra-row weeding

The following alternatives to perform intra-row weeding have been taken into consideration:

- *Mechanical.* Weeds can be cut or removed from the soil by mechanical actuators. Actuators for intra-row weeding are described by several authors [19,25,18,26–28]. Some of them are specially designed for operation in sugar beet [19,18]. A disadvantage is the inertia of the mechanics limiting the capacity of the machine.
- *Air.* Pressured air can be used to remove weeds from the intra-row area. Lütkemeyer [29] applied pressured air through two horizontal air nozzles at both sides of the crop row about 2 cm under the soil surface, removing weeds from the intra-row area when moved in row direction.
- *Flaming.* The plants in the field are exposed to flames generated by burning fuel in such a way that the heat injury causes the weeds to die but the crop plants to survive [30]. Recently developments are reported on intra-row flaming with an array of small burners that can be turned on and off rapidly [31].
- *Electrical discharge.* Weeds can be killed by producing an electrical discharge. Blasco et al. [32] applied an electrode producing electrical discharges of 15 kV and 30 mA during 200 ms for a single leaf. The system was able to eliminate 100% of the small weeds, but on bigger plants only the affected leaves showed some kind of damage. Safety with these high voltages is also a concern.
- *Hot water.* Weeds are exposed to hot water so that heat injury causes the weeds to die. Hansson and Ascard [33] conclude that hot water weed control has potential on urban surfaces and railroad embarkements.
- *Freezing.* Weeds can be killed by freezing them.
- *Microwaves.* Weeds can be killed by exposing them to microwave radiation [34].
- *Infrared.* Thermal weed control can be applied using infrared radiation [35].
- *Laser.* Laser can be used as a weed stem cutting device or for stopping or delaying weed growth by directing a laser towards the apical meristem the weeds [36]. A laser can not cut below ground surface, and has, therefore, minor effect on certain weed species. On the other hand, not moving the soil prevents buried seeds from germinating. High power laser is needed to reach reasonable performance, and this involves high costs [37].
- *Water-jet.* Weed stems can be cut with high-pressure water-jets. Warner [38] investigated water jet cutting as a possible means for thinning of row crops. In a field experiment with seedlings with 1.5 mm thick stems about 60–70% of the seedlings were damaged. But with 3 mm thick stems there was virtually no effect. Water jet cutting for intra-row weeding needs more investigation before it can be applied.

Flaming, hot water, infrared, freezing, microwaves and pressurized air are normally applied non-targeted. The effect of these techniques is based on a difference between crop plants and weeds in resistance to the applied dosage. Non-targeted application will always harm the crop and will not replace hand weeding totally. Targeting these techniques just to the weeds, without damaging the crop, is expected to be difficult in the intra-row area because the weeds are growing close to the crop plants. From the techniques that can be targeted to the weeds only, mechanical actuators are still the most proven solution despite its limited capacity due to inertia. Therefore, a mechanical actuator was chosen as working principle for intra-row weeding. However, further investigation is needed to segmented weeding where one of the cheaper, less precise approaches are used far from the crop and an expensive, more precise technique is applied nearer to the crop stems.

2.3.4. Determine if within field

The determination whether the weeding robot is located within the field or not, needs to be correct at any time. The following alternatives were taken into consideration:

- *GPS.* Given the coordinates of the field boundary, GPS signals can be used to decide whether the robot is located inside or outside the boundary. The inaccuracy is less or equal to the sum of the inaccuracies of measuring the field boundary and the accuracy of the GPS receiver used on the robot. Dead reckoning could improve the accuracy of position measurement.
- *Machine vision and dead reckoning.* Machine vision combined with dead reckoning can detect the absence of plants at a forward distance and from this it could be concluded whether the robot is still in the area where crop plants are growing or not. Åstrand and Baerveldt [17], Tillett et al. [8] and Pilarski et al. [2] used this technique for detecting the end of rows.

GPS was selected to determine whether the weeding robot is within the field or not, because it is more reliable.

2.3.5. Navigate along the row

The following alternatives are taken into consideration for navigating along the crop rows:

- *GPS.* When the absolute location of the rows are known from sowing [15], the robot can follow this predetermined route based on GPS. Commercial RTK GPS automatic tractor guidance systems claim to be capable of steering with precision errors of 25 mm from pass to pass [39]. O'Connor [3] tested the accuracy of navigation with CDGPS (Carrier-phase Differential GPS) and found a mean error of 0.83 cm and a standard deviation of 1.22 cm over a driving distance of 50 m at a speed of 0.33 m/s, while the ordinary GPS measurements over the same distance showed a mean error of 0.38 cm and a standard deviation of 1.32 cm. Major drawbacks of using GPS systems are: the performance can be affected by objects around a field like trees obscuring the radio signals from the satellites; and the difficulty in dealing with the yearly changing row locations and the high costs of high accuracy.

- *Machine vision.* Machine vision algorithms can detect crop rows in real time. The relative position and orientation of the robot to the row can be used as input for tracking the crop row. Although weed density, shadows, missing plants and other conditions degrade the performance of machine vision guidance systems, some researchers have been successful in row detection in sugar beet [40,41,17,42].
- *Tactile sensors and dead reckoning.* A tactile sensor guided by the crop row can be used to indicate the relative position and orientation of the crop rows to the robot [43]. The relative position of the robot to the row can be used as input for tracking the crop row. A drawback is that tactile sensors can harm the crop.
- *Ultrasonic sensors and dead reckoning.* Ultrasonic sensors can measure the distance of the robot to the crop row. From multiple ultrasonic sensors or from combining ultrasonic sensor information with dead reckoning the relative position and orientation of the robot to the crop row can be determined. The relative position of the robot to the row can be used as input for tracking the crop row.
- *Optical sensors and dead reckoning.* Optical sensors can measure the distance of the robot to crop plants in the row. From multiple optical sensors or from combining optical sensor information with dead reckoning the relative position and orientation of the robot to the crop row can be determined. The relative position of the robot to the row can be used as input for tracking the crop row.

With machine vision the weeding robot can work in any field without requiring absolute coordinates of a path to be followed. Absolute positioning by means of GPS, possibly combined with other sensors, requires knowledge of the absolute position of crop rows in a field. Tactile sensors are not going to be used because in case of sugar beet they could harm the crop. Machine vision is preferred over ultrasonic or optical sensors, because of the ability to look forward, which contributes to a more accurate control of the position of the weeding robot relative to the crop row. Though dead reckoning could contribute to the navigation accuracy, exclusive machine vision was selected for navigation along the row, because it was expected to be sufficient.

2.3.6. Determine if on headland

The following alternatives were taken into consideration to decide whether the robot is on headland:

- *GPS.* Given the coordinates of the headland boundary, GPS can measure whether the robot is located inside or outside the headland boundary. Dead reckoning could improve the accuracy of position measurement with GPS.
- *Machine vision.* Machine vision combined with dead reckoning can detect the absence of plants at a forward distance and from this it could be concluded whether the robot is still in the area where crop plants are growing or not [17,8,2]. Pilarski et al. [2] report a prediction accuracy of 90% during cutting 40 ha of alfalfa and sudan crop, meaning that in 10% of the cases the headland was not detected. False positives also occasionally occurred. Tillett et al. [8] detected the end of row in transplanted cauliflower with machine vision and dead reckoning. Setting an approximate row length was required to avoid premature turns.
- *Ultrasonic sensors and dead reckoning.* Ultrasonic sensors can measure the distance of the robot to crop plants in the row. Increased distances over a certain driven distance can indicate absence of plants and can indicate that the robot arrived at the headland.
- *Optical sensors and dead reckoning.* Optical sensors can measure the distance of the robot to crop plants in the row. Increased distances over a certain driven distance can indicate absence of plants and can indicate that the robot arrived at the headland.

Tactile, ultrasonic or optical sensors in combination with dead reckoning can not guarantee a correct detection of the end of row when another crop grows on the headland – for instance when seeded to prevent germinating of weeds – and, therefore, also can not guarantee a correct headland detection. Machine vision could give more reliable results. But because the headland management is inconsistent in practice, the resulting variety of headland vegetation makes reliable vision perception too difficult. Therefore, GPS was selected to determine whether the weeding robot is located on the headland. Using GPS requires some labour for recording the border of the headlands in advance, but will result in correct headland detection. In order to avoid additional software for combination with dead reckoning needed to achieve sufficient accuracy with ordinary GPS, a high accuracy GPS has been selected.

2.3.7. Navigate on headland

On the headland the weeding robot has to make a turn and position itself in front of the next rows to be weeded. The following alternative strategies were taken into consideration:

- *GPS.* The path is planned at the moment the robot arrives at the headland or as soon as the headland is identified. Navigating along this path can be done by GPS. Thuilot et al. [44] show that it is possible to follow a curved path with a tractor relying on a single GPS receiver. Dead reckoning could improve the accuracy of position measurement with GPS.
- *Dead reckoning.* The headland turn is made by following a planned path as soon as the robot arrives at the headland. This dead reckoning can be performed via a vehicle Kalman filter. Tillet et al. [8] showed that a maximum error measured as the normal distance between the commanded and measured path was around 60 mm.
- *Machine vision and dead reckoning.* Headland turns performed by dead reckoning could be improved by detecting crop rows with a forward looking camera to align the robot with the crop rows.

Accuracy of dead reckoning will decrease with the length of the turning path and in situations where more slip occurs. Absolute position measurement by GPS does not have this drawback. Therefore, GPS was chosen to navigate on headland.

2.3.8. Locomotion related functions

The following alternatives in terms of locomotion related functions were taken into consideration. All options in each row in the morphological chart are discussed together.

- *Energy supply.* The high energy content of fuel makes a fuel as energy source still very practical for energy consuming treatments that have to be performed in agriculture. Another option is to supply the robot with energy via an electric power point charging batteries mounted on the robot. The robot could also obtain its energy from the sunlight via solar panels.
- *Energy conversion.* Energy can be converted into movement by a gas engine, a diesel engine or by an electric engine. A diesel engine is the most common engine used in agriculture. However, gas engines or electrical engines could be used as well.
- *Transmission of movement.* The engine movement could be transferred to the wheels by a standard mechanical transmission like used in conventional tractors, but also by a continuously variable transmission incorporating both mechanical and hydraulic parts like those introduced in recent tractor models. Hydrostatic transmissions have lower energy efficiency than the previous alternatives, but are still a proven concept in agricultural machines that require not so much traction force.
- *Traveling gear.* Three wheels, four wheels, two tracks or four tracks would be alternative travelling gears for a robot. The most important advantages of tracks compared to wheels are the better traction and the lower soil compaction. Disadvantages are the higher costs, less suitability for driving on hard surfaces and damage to the soil in sharp turns due to skid steering. Therefore, tracks are normally applied only for heavy machinery or for special purpose machinery for soft surfaces [45].

From the alternatives, a diesel engine with a hydraulic transmission was selected for the locomotion related functions, because it is a proven concept in agriculture. A gearbox would limit the choice of driving speed and shuffling would be difficult to automate. A continuously variable transmission was, therefore, preferred over a gearbox. Hydraulics makes it possible to design a compact wheel construction preventing damage to the crop.

A design with four wheels is preferred over one with three wheels because of stability. Four wheels were also preferred over two or four tracks. It is expected that if four wheels are used for such a light-weight vehicle (not more than 1500 kg) soil compaction would be acceptable. Traction when using wheels is expected to be good enough because of limited need of traction for intra-row weeding. Four wheel drive and four wheel steering were chosen to have the possibility to investigate all kinds of driving strategies, which best meets the requirement to design a platform suitable for research.

2.3.9. Communication with the user

The communication between robot and user differs in who is taking the initiative for communication, the type of information to be exchanged and in the distance of the user to the robot. The following communication related functions were distinguished:

- *Input of robot settings.* The robot should be put into operation by the user after it was brought to the field. Robot, task and field specific settings must be set.
- *Sending status information at request*. The robot sends information about its operational status at remote user request (e.g. the progress of the execution of its task).
- *User notification*. The robot takes the initiative to inform the remote farmer (e.g. when stopped due to security reasons or when it is ready).

For each of the functions, the following alternatives were taken into consideration:

- *Board computer.* A computer with a user interface mounted on the robot could be used as a means to input data settings like the row distance. It could also display notifications status information on a user request.
- *SMS.* Information between the robot and the user could also be exchanged by Short Message Service (SMS) messages [46,47].
- *PDA.* Dedicated software running on a PDA could be a means to exchange information between robot and user via the internet.
- *PC.* Information between the robot and the user could be exchanged by dedicated software running on a PC.

- *Webpage.* Information between the robot and the user could be exchanged by updating a database on a webserver. A webpage would be accessible via mobile phones, PDA or PC.

If the user is near the robot, the most reliable method for user robot communication is communication via a board computer. Therefore, a board computer was selected for input of robot settings. In the Netherlands any place is covered by the GSM network. Every modern cell phone can use SMS and in practice, most messages arrive fairly quickly. Therefore, SMS was selected for user notification. A webpage gives good opportunities to represent information in a well arranged way and it is easily accessible from everywhere. From the alternatives a webpage was selected for sending status information at request.

2.3.10. Detect unsafe situations

The following alternatives were taken into consideration for detection of unsafe situations:

- *Super canopy front and rear.* Unsafe situations can be detected by detecting obstacles above the crop plants at the front and rear side of the robot by e.g. laser scanner, stereovision, millimeter wave radar or ultrasonic sensors [48,49]. Any obstacle detected is classified as an obstacle causing an unsafe situation. While the robot can move sideways, the prevailing driving direction will be forward, followed by reverse. Objects in between the crop plants would not be detected.
- *Super canopy circumferential.* Unsafe situations can be detected by detecting obstacles above the crop plants at all sides of the robot by e.g. laser scanner, stereovision or ultrasonic sensors. Objects in between the crop plants would not be detected.
- *Sub canopy front and rear.* Unsafe situations could be detected by detecting obstacles in between crop plants at the front and rear side of the robot. However, this requires detection techniques for discrimination between crop and other obstacles, and classifying the latter into obstacles to stop for and obstacles not to stop for. While there is some interesting research in this area, this problem is not yet solved [50,51].
- *Sub canopy circumferential.* Detecting obstacles in between crop plants at the front and rear side of the robot could be extended to detection at all sides of the robot.

Ideally the weeding robot should detect every unsafe situation, at every level and direction. Even if somebody is lying in between the crop rows below canopy level this should be detected. Because of the costs for such a solution, circumferential super canopy detection was chosen to provide a basic level of safety.

3. The vehicle

This section describes how the concept solution is worked out in detail. The resulting versatile platform is shown in Fig. 4.

The size of the vehicle was determined by the standard track width used for mechanical weeding in sugar beet in the Netherlands which is 1.50 m. This track width also makes the design versatile in the sense that it is suitable for crops grown in beds like carrots and onions.

Sugar beets are grown at a row distance of 50 cm so the weeding robot covers three rows. The engine power is chosen so that sufficient capacity is available for driving and steering under field conditions and for operating three weeding actuators. The required power for the actuators

Fig. 4. The platform.

was calculated based on an actuator specially designed for intra-row weeding by Bontsema et al. [19]. The engine is a 31.3 kW Kubota V1505-T.

The ground clearance is about 50 cm to prevent the crop from being damaged by the vehicle. The vehicle is 2.5 m long to have enough space for mounting actuators under the vehicle in the middle between the front and rear wheels. The tire width of 16 cm leaves enough space for steering in-between crop rows while soil compaction is expected to be acceptable. The weight of the vehicle is about 1250 kg.

The engine powers a hydraulic pump. It supplies the oil for steering and driving, while another pump can be mounted for driving the actuators. The oil for driving and steering flows to an electrically controllable valve block with eight sections. Four sections are used for steering and four are used for controlling wheel speed, so wheel speeds and wheel angles can be controlled individually. The wheels are driven by radial piston motors. The driving speed ranges from 0.1 to 1.8 m/s. A maximum travel speed of 3.6 m/s for fast moving of the robot from field to field could be realized by switching to two wheel drive by combining the oil flows of four wheels into two flows.

Each wheel is steered by a hydraulic motor with a planetary reduction gear. The maximum steering speed is 180 deg/s. The angles of the wheels are measured by angle sensors. The oil for driving the wheels flows via a turnable oil throughput. This makes it possible to turn the wheels in any angle from 0° to 360°.

The weeding robot electronics consists of six units connected by a Controller Area Network (CAN) bus using the ISO 11783 protocol. In Fig. 5 a schematic overview of this system is given with vehicle control related sensors and valves. In every wheel a cogwheel is mounted with 100 cams thus giving 100 pulses per revolution via magneto-resistive sensors. Per wheel two of those sensors are mounted such that their signals are 90° out of phase, thus permitting both speed and direction detection. Per wheel steering unit an analogue angle sensor is mounted with an accuracy of 1° and a range of 180°. The sensors are connected to four micro controllers located near the four wheels which transmit the wheel speeds and the wheel angles via the CAN bus. A laptop processes images supplied by the front sight camera and transmits the location of the crop rows in relation to the vehicle position in a CAN bus message. An embedded controller running a real time operating system (National Instruments PXI system) also connected to the CAN bus performs the vehicle control. The GPS receiver and a radio modem are connected with the PXI via RS232. The radio modem interfaces the remote control used for manual control of the weeding robot. The PXI system gathers wheel angles, wheel speeds, crop row location data, GPS data and remote control data and controls the vehicle by sending messages to two micro controllers connected to the valve block. The user interface of the weeding robot software running on the PXI system can be visualized on a laptop via a wireless connection (Ethernet). Besides the sensors that are directly related to navigation and control, there are some more sensors connected to the modules. These sensors, indicating oil filter status, oil temperature and oil level are also interfaced to the PXI via the micro controllers and the CAN bus. In case a sensor indicates an emergency, the weeding robot will switch off automatically. Devices for the communication related functions and for obstacle detection are projected but not mounted yet.

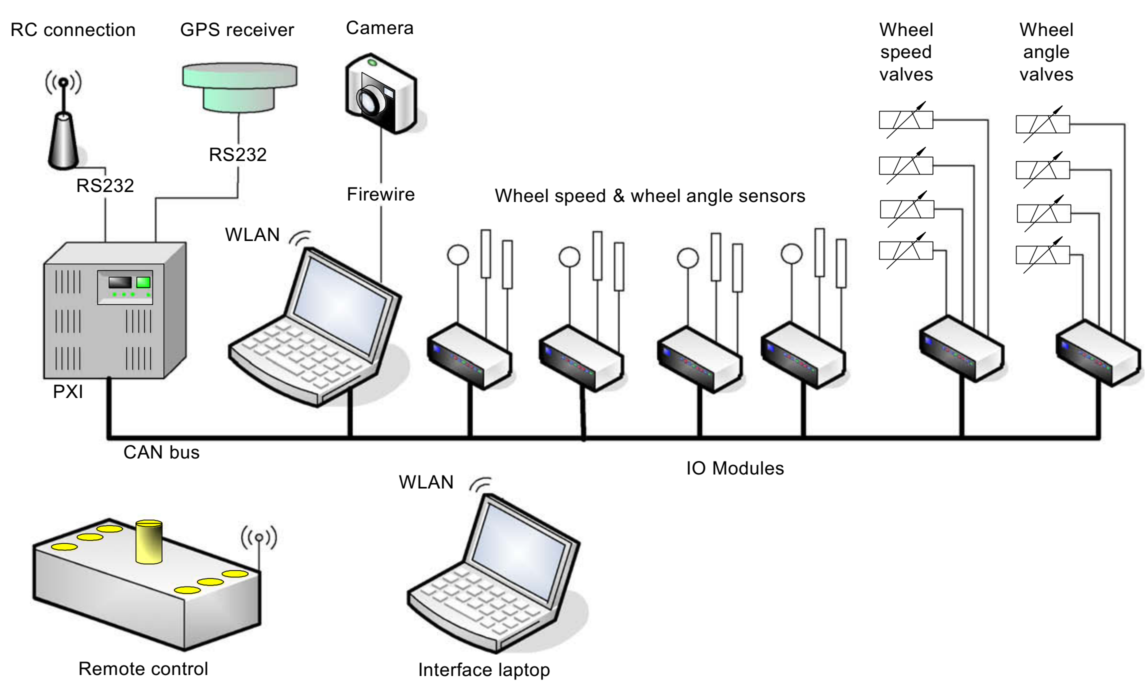

Fig. 5. Electronics architecture.

4. Discussion and conclusions

The research vehicle was designed using a structured design method. The advantage of using this method is that it clearly structures the design process. It provides a good overview of the complete design and because of the structured sequence of design activities, it is easy to keep track of the progress of design. Another advantage of the structured design method is that it forces the designer to look at alternative solutions and this decreases the probability of heuristic bias and increases the quality of the outcome. Although the designer is forced to thoroughly judge the identified alternative solutions when selecting the final concept, the outcome is still depending on the available knowledge of the designer about the alternative solutions. So, while the method can not guarantee that the absolute best solution possible will be selected, it certainly is superior to a trial and error approach. In a research context it is easy to identify alternative subjects that are worthwhile to investigate further, while in the same time the main line of the research remains clear.

The result of the design is a versatile research vehicle with a diesel engine, hydraulic transmission, four wheel drive and 360° four wheel steering. The robustness of the vehicle and the open software architecture permit the investigation of a wide spectrum of research options regarding solutions for intra-row weed detection and weeding actuators. The result of the design is a reliable concept for an autonomous weeding robot in a research context.

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