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A Robot to Detect and Control Broad-Leaved Dock (*Rumex obtusifolius* L.) in Grassland

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Broad-leaved dock is a common and troublesome grassland weed with a wide geographic distribution. In conventional farming the weed is normally controlled by using a selective herbicide, but in organic farming manual removal is the best option to control this weed. The objective of our work was to develop a robot that can navigate a pasture, detect broad-leaved dock, and remove any weeds found. A prototype robot was constructed that navigates by following a predefined path using centimeter-precision global positioning system (GPS). Broad-leaved dock is detected using a camera and image processing. Once detected, weeds are destroyed by a cutting device. Tests of aspects of the system showed that path following accuracy is adequate but could be improved through tuning of the controller or adoption of a dynamic vehicle model, that the success rate of weed detection is highest when the grass is short and when the broad-leaved dock plants are in rosette form, and that 75% of weeds removed did not grow back. An on-farm field test of the complete system resulted in detection of 124 weeds of 134 encountered (93%), while a weed removal action was performed eight times without a weed being present. Effective weed control is considered to be achieved when the center of the weeder is positioned within 0.1 m of the taproot of the weed—this occurred in 73% of the cases. We conclude that the robot is an effective instrument to detect and control broad-leaved dock under the conditions encountered on a commercial farm. © 2010 Wiley Periodicals, Inc.

1. INTRODUCTION

Broad-leaved dock (*Rumex obtusifolius* L.; Figure 1) is a common and troublesome weed with a wide geographic distribution (Cavers & Harper, 1964). If broad-leaved dock is not controlled, it will reach a high density and reduce grass yield by 10%–40% (Courtney, 1985). The weed is readily consumed by livestock, but its nutritive value is less than that of grass (Oswald & Haggar, 1983). Land that is free of broad-leaved dock can be newly infested when manure containing viable seeds is spread on the land, by spreading the sludge that is produced when drainage canals are dredged, and through seeds in bird droppings.

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Figure 1. A single plant of broad-leaved dock (*Rumex obtusifolius* L.) in a pasture. The pictured plant has a diameter of approximately 0.6 m and is starting to flower.

In conventional farming, the weed is normally controlled by using the selective herbicide MCPA (2-methyl-4-chlorophenoxyacetic acid). In organic farming no synthetic pesticides are used, and there is a risk that broad-leaved dock will spread. On 17 organic dairy farms in The Netherlands, 51% of fields were infested at more than 1,000 plants ha^{-1} [one hectare (ha) equals 10,000 m^2] (Van Middelkoop, De Visser, & Schilder, 2005). Of 108 organic farmers in Germany, 85% indicated having problems with broad-leaved dock (Böhm & Verschwele, 2004). Consequently, some farmers wanting to switch from conventional farming to organic farming report that they refrain from doing so because they fear that broad-leaved dock will spread beyond control (Edith Finke, agricultural advisor, DLV, personal communication, 2008). Thus, broad-leaved dock may turn out to be a serious obstacle to achieve the Dutch government's goal of having 10% of land farmed organically from 2010. This is so even though the price of organically produced milk is higher than the price of conventionally produced milk.

If no herbicide is to be used, broad-leaved dock can be controlled by removing plants or destroying them, possibly in combination with grassland renewal and rotation with a grain crop (Van Middelkoop et al., 2005). Manual removal of the plants may require several hundred hours per year on a single farm (Finke, personal communication). Frequent cutting alone is insufficient to prevent broad-leaved dock from spreading (Niggli, Nosberger, & Lehmann, 1993). A review of nonchemical means to control broad-leaved dock is given by Bond, Davies, and Turner (2007).

Robots have been proposed by many workers to reduce the cost and increase the focus of agricultural operations (e.g., Blackmore, Stout, Wang, & Runov, 2005). A robot that can detect broad-leaved dock and control it in a nonchemical way will address the problem of organic dairy farmers. Robots are already being used in some form in agriculture. Robots that milk cows are common in The Netherlands and the United States. There is a robot to transplant cuttings for vegetative propagation (Rombouts & Rombouts, 2002; also see http://www.rombomatic.com). Robots to control weeds in arable farming and field vegetable production have great application potential because of the large areas to be worked and because of the large investment to control weeds. To the best of our knowledge, there are not yet any commercially available robots for weed control or for other tasks in arable farming, although experiments have been ongoing for a number of years and prototypes exist for intrarow weeding in sugar beet (Åstrand & Baerveldt, 2003), hoeing of row crops (Bakker, Wouters, van Asselt, Bontsema, Tang, et al., 2008), detection of volunteer potatoes in corn (Van Evert, Van der Heijden, Lotz, Polder, Lamaker, et al., 2006), and weeding in cauliflower (Tillett, Hague, & Marchant, 1998).

This paper describes a robot to detect and control broad-leaved dock. Detection of broad-leaved dock in grassland pasture has been studied by Dürr, Anken, Bollhalder, Sauter, Burri, et al. (2004), Gebhardt and Kühbauch (2007), Gebhardt, Schellberg, Lock, and Kühbauch (2006), Holpp, Anken, Šeatović, Grüninger, and Hüppi (2008), Šeatović (2008), Šeatović, Kutterer, Anken, and Holpp (2009), and Van Evert, Polder, Van der Heijden, Kempenaar, and Lotz (2009). In addition, texture-based discrimination between grassy and broad-leaved weeds on a soil background was described by Ishak, Hussain, and Mustafa (2009) and by Tang, Tian, and Steward (2003). A review of autonomous weed control (guidance, detection, control) is given by Slaughter, Giles, and Downey (2008).

Various methods to control broad-leaved dock have been suggested: mechanical destruction (Böhm & Finze, 2004; Finze & Böhm, 2004), microwaves (Dürr et al., 2004; Latsch, Sauter, Hermle, Durr, & Anken, 1999), and cultural measures (Van Middelkoop et al., 2005). Navigation on agricultural fields has been studied by Bakker, Van Asselt, Bontsema, Müller, and Van Straten (2006).

Challenges to the introduction of robots into agriculture are scientific and technical in nature, as well as related to performance, economic, safety, and social issues. Scientific challenges lie in robust self-localization and detection of objects in an environment that is by its nature highly variable, at most semistructured, and may contain unexpected obstacles. Technical challenges lie in actuation of, for example, grippers for harvesting or implements for weed removal. An agricultural robot will have to be reasonably accurate because it is simply not acceptable, for example, to remove a row of sugar beet plants while weeding. And a robot will have to offer a clear economic benefit, in terms of either savings on labor, increased work speed, or higher quality of the product (Pedersen, Fountas, Have, &

Blackmore, 2006; Sorensen, Madsen, & Jacobsen, 2005). Finally, agricultural machinery is typically quite powerful, and this places strict requirements on the safety of a robot.

A robot offers the unique opportunity to work continuously and slowly—and thus precisely—because it can operate without human presence. As the constraint of labor time disappears, the aspects of farm organization that are preconditioned on that constraint may be changed. This may require changes in the way the work is organized or crops are grown (e.g., Bleeker, Van der Schans, & Van der Weide, 2007), and this gives rise to a final challenge, namely the willingness and the ability of farmers to accept the robot and reorganize the farm. In some situations it may be possible to introduce into current farm practice a robot as a substitute for human labor (Foglia & Reina, 2006). Often, however, introducing a robot into farming will be different from simply replacing a human or upgrading to the next bigger machine, precisely because a robot is autonomous.

The challenges attached to introducing agricultural robots are illustrated by the fact that research going back at least 20 years (e.g., Bonicelli & Monod, 1987; Hague & Tillett, 1996; Reid, Zhang, Noguchi, & Dickson, 2000; Tillett et al., 1998) has led to only a few commercial robots in greenhouse farming. The "Automaatje" robot for arable farming (Thoma, 2005; Van Zuydam & Achten, 2002) has been tested in the field and is available commercially but, as far as we are aware, it has not been sold. Recent reviews of robots in agriculture do not mention any commercially available weeding robots (Billingsley, Visala, & Dunn, 2008; Slaughter et al., 2008). Indeed, Tillett, Hague, Grundy, and Dedousis (2008) believe that it will take 10 years or more before robots for arable farming are used.

The objective of our work was to develop a robot that can navigate a pasture, detect broad-leaved dock, and remove any weeds found. The remainder of this paper is organized as follows. In Section 2 we describe the design and construction of the robot. In Section 3, experimental results are described. Section 4 discusses the results, and in Section 5 we draw our conclusions.

2. DESIGN AND CONSTRUCTION OF THE ROBOT

The design of the robot was guided by the following criteria:

1. The robot was deemed to be useful if it can remove 70% of broad-leaved dock plants because then repeated application of the robot will keep the weed under control. A control rate of 60%–80% has been reported by Finze and Böhm (2004) with a method first proposed by Riesenhuber (Böhm & Finze, 2004; Van Eekeren & Jansonius, 2005). The method consists of a rod weeder that is driven into the ground and that fragments the weed's taproot. An advantage of this method is that no soil or plant material is transported, so the method will not result in inadvertent spreading of the weed. Selection of the Riesenhuber method means that the robot needs to have a fairly large power source to power the weeder. The mass of the robot needs to be sufficiently large to be able to push the weeder into the ground. This, combined with the weight of the power source, means that the robot has to be a sturdy vehicle.
2. Presence of broad-leaved dock is considered a problem when its density exceeds 1,000 plants ha^{-1}. In practical situations, the density may exceed 5,000 plants ha^{-1}. Broad-leaved dock often occurs in patches, where single plants grow in close proximity to one another but can still be distinguished as individuals. A pasture may contain several such patches as well as many individual plants. Typically, the robot will therefore have to search the entire pasture.
3. Pastures are typically free of obstacles, and tight maneuvering is not required.
4. The robot will have to be capable of many hours of continuous operation and must thus carry a large energy store.
5. The work rate is not critical, because weeds can be detected and controlled from late April to October.
6. Cost is an issue. The robot will have to provide an economic benefit.
7. The robot will mostly be used in polders (reclaimed land), where pastures are separated by water-filled drainage ditches from adjacent pastures and from the road; thus escape from the field is not a concern.
8. Polders have a shallow water table (0.2–0.5 m), as a consequence of which the soil is often wet. Damage by using heavy machinery or slipping should be minimized.

2.1. Platform

The above considerations led to the following design (Figures 2 and 3). The robot's base consists of a rigid frame of 1.25 × 1.11 m to which four independently driven wheels are attached. The wheels are fitted with 18 × 8.50-8 golf cart tires (diameter 0.44 m, width 0.18 m) that are designed to provide traction on grass while minimizing impact on the sod. Skid steering was implemented in order to keep construction light and inexpensive. Power is provided by a 36-kW diesel engine (Kubota Corp., Osaka, Japan). Each wheel is driven independently by a hydrostatic motor, but the wheels on each side are connected hydraulically in such a way that they rotate at the same speed. This four-wheel drive prevents wheel slipping.

Hydraulics are controlled by a sixfold proportional valve block. This block can be operated manually, but during robotic operation the valves are controlled through a programmable logic controller (PLC; Ecomat 100, IFM Electronics GmbH, Essen, Germany). A safety feature of the valve block is that when electrical power fails, all hydraulic valves go to neutral state. Further safety is provided by an emergency switch on the robot that interrupts power to the diesel engine's fuel pump.

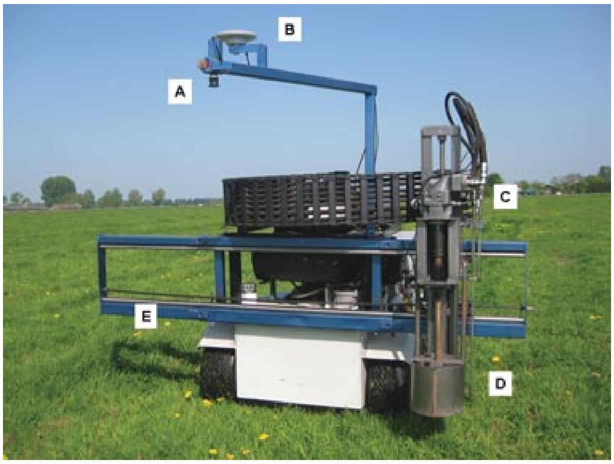

Figure 2. The completed robot. Visible are (A) the boom-mounted camera, (B) the GPS antenna, (C) the hydraulic motor for the weeder, (D) the weeder, and (E) the rail that allows lateral movement of the weeder.

The PLC receives inputs from incremental encoders mounted on the wheels, from a remote control receiver, and from the PC that provides overall control of the system. The wheel encoders (360 pulses per revolution) are used to regulate the robot's driving speed. The encoder counts are input to separate PID (proportional–integral–derivative) controllers for the left and right wheels. To prevent jerking movements when starting, the PLC program implements logic that limits the acceleration of the robot to 0.05 m s^{-2}. The remote control receiver is connected to a six-channel remote control transmitter; the signals can be used to control a variety of functions, including manual override of the speed. The PC provides overall control of the system and functions as a preprocessor of the signals from the global positioning system (GPS) receiver and the vision system.

Weeds are detected using machine vision. The vision system consists of a camera attached to a boom in front of the robot. The camera's field of view extends from the position of the weeder forward. The camera is a Marlin F201C (Allied Vision Technologies GmbH, Stadtroda, Germany), and the lens is a Cinegon 4.8 mm (Schneider Optische Werke GmbH, Bad Kreuznach, Germany). The camera is mounted at a height of 1.6 m, resulting in a viewing area on the ground of 2.20 × 1.65 m. Images are taken with a resolution of 1,600 × 1,200 pixels, resulting in a resolution on the ground of ~1.5 mm per pixel.

The overall dimensions of the robot (including boom) are approximately 2.50 × 1.15 m, with a height of 1.5 m (the highest point of the boom is 2.0 m). The overall weight of the robot is approximately 500 kg.

2.2. Path Following

For the purpose of detecting and removing broad-leaved dock in a pasture, it is sufficient that the robot follow a predefined path; autonomous path planning is not required. A dual-frequency GPS/GLONASS receiver (AsteRx 2, Septentrio, Leuven, Belgium) was used to determine the robot's position. Real-time kinematic (RTK) precision (±1–2 cm) was obtained by using correction signals from a commercial network of base stations (Quality Positioning Services B.V., Zeist, The Netherlands). The network consists of 35 base stations that cover the entire country, and the correction signals are transmitted through Universal Mobile Telecommunications System/general packet radio service (UMTS/GPRS). The receiver outputs the robot's position expressed in WGS84 coordinates. These

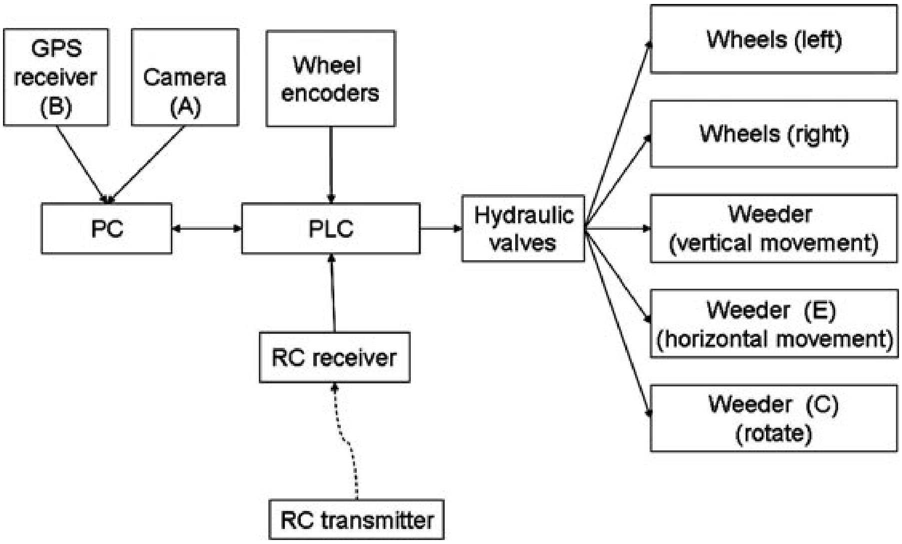

Figure 3. Major components of the robot and their connections. Letters indicate the locations of components in Figure 2.

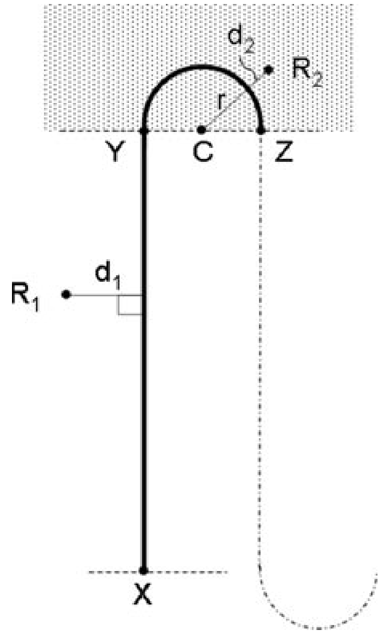

Figure 4. The robot follows a path that consists of line and arc segments. Symbols are explained in the text.

are transformed to the rectangular Dutch national datum (Rijksdriehoeksmeting; RD), which is the coordinate system used for topographical maps in The Netherlands. A simplified transformation from WGS84 to RD was implemented that disregards tectonic plate movement but is adequate for our purposes, as described by Strang van Hees (2006). The implementation is based on the "rd2wgs" program (E.J.O. Schrama, Delft University of Technology, personal communication, 2008).

Currently, paths are limited to an alternation of line segments and arcs (Figure 4). In Figure 4, the robot starts at X and travels through Y to Z and beyond. Every time a new position estimate is received, the distance from that position to the current segment is used to generate a steering signal. When the robot is at position R_1, the distance to the line segment is d_1. When the robot exits line segment XY (i.e., when it enters into the half-plane defined by the line YZ and that does not contain X), it starts to follow the arc YZ. When the robot is at position R_2, the value of the distance to the segment (d_2) is defined as $| \|R_2C\| - r|$, where C is the center of arc YZ and where the sign is positive when the robot needs to turn to the right to regain the planned path and where the sign is negative when the robot needs to turn to the left. The error in the robot's position is thus easily calculated as either the perpendicular distance to a line segment or the distance to a circle. Steering is effectuated with a PID controller implemented in the PC program.

The GPS antenna is placed on the camera boom, which extends in front of the robot. Thus, when the robot is on the planned path and starts to deviate, this will immediately result in a large measured position error, which in turns allows for rapid correction.

The robot is not equipped with inertial navigation to complement the GPS position estimate. When a GPS signal cannot be received, the robot stops until the GPS signal is available again.

2.3. Weed Detection

Broad-leaved dock plants are detected using machine vision with a slightly modified version of a texture-based method developed earlier (Polder, Van Evert, Lamaker, De Jong, Van der Heijden, et al., 2007; Van Evert et al., 2009). The method is based on the observation that grass leaves are long and narrow (several millimeters), whereas the leaves of broad-leaved dock are at least an order of magnitude larger. Consequently, image parts with grass contain more color and intensity transitions than image parts with broad-leaved dock. This texture information can be used to discriminate between grass and broad-leaved dock.

The weed detection method is illustrated in Figure 5. Briefly, it consists of the following. A downward-looking camera is used to take a color image (with pixel size $\sim 1.5 \times 1.5\ \text{mm}^2$). The color image is transformed to a monochrome image using the method of Marchant, Tillett, and Onyango (2004) to account for varying illumination. The resulting (monochrome) image is divided into subimages (tiles), and each tile is subjected to two-dimensional Fourier analysis. A systematic analysis showed that a tile size of 8×8 pixels was optimal and that the sum of equally weighted Fourier coefficients for all spatial frequencies above zero in each tile yielded a suitable measure to discriminate between grass and weed (Van Evert et al., 2009). High values are likely to correspond to an image tile with grass and low values to weed. A binary image was obtained by applying a threshold. In this binary image, weed pixels that are not linked to other weed pixels are removed from the image. Then, clusters of adjacent weed pixels are joined through a morphological closing operation. Any remaining object is considered to represent a weed. The centroid of each object is taken as the location of the taproot of the detected weed. With this method, Van Evert et al. (2009) detected 89% of weeds in their data set.

As the robot moves toward a weed, that weed will typically appear in several successive frames, the number of which depends on the frame rate of image processing and the driving speed of the robot. Also, more than one weed may appear in a single frame. Individual weeds are tracked from frame to frame through nearest-neighbor matching. Knowledge about the position of each image along the robot's path is used to help make the match.

2.4. Weed Control

Weed control is effectuated with a vertical rod weeder (Finze & Böhm, 2004). The weeder consists of a single

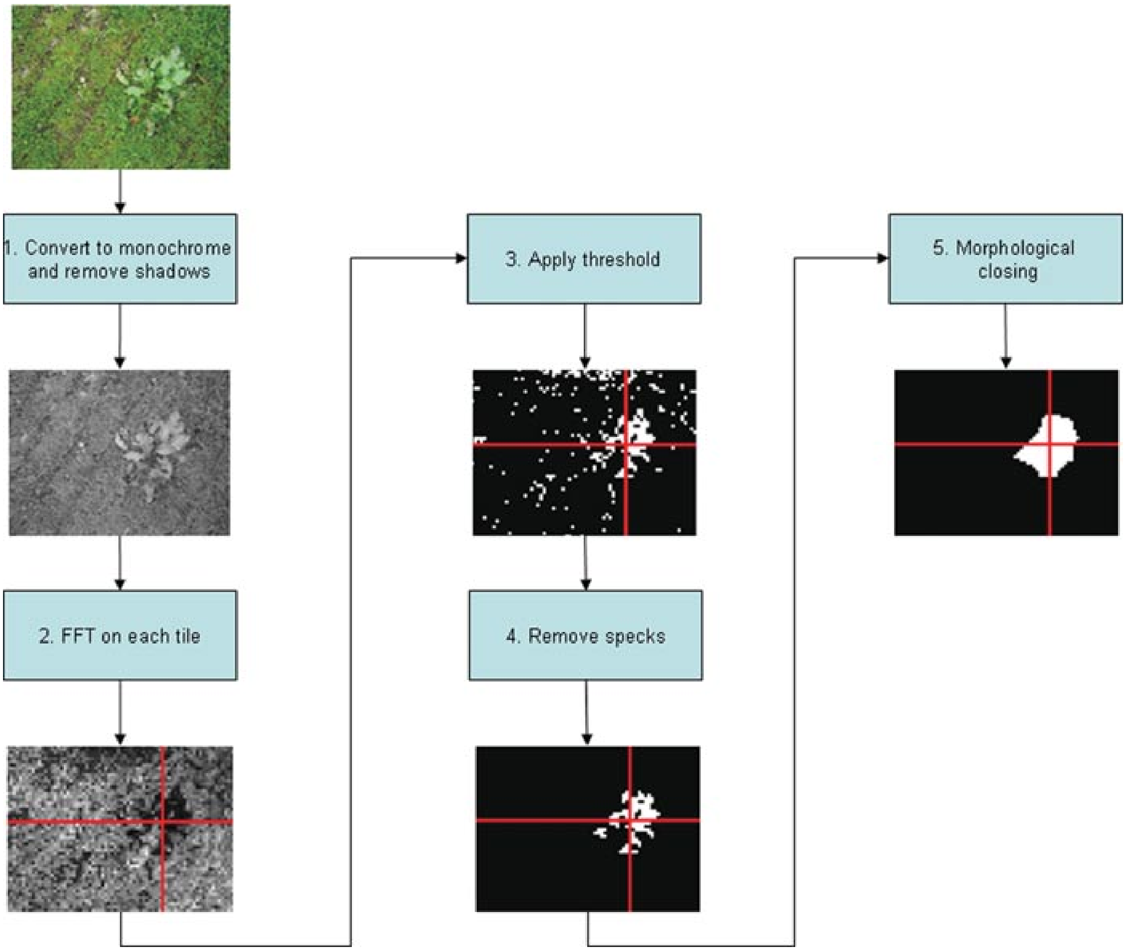

Figure 5. Flowchart of the steps in image processing.

0.20-m blade that rotates around a vertical axis and is pushed into the ground at the location of the weed (Figure 6). To facilitate entry of the blade into the soil, the vertical axis extends below the blade and ends in a sharp point. The size of the cutting blade ensures that adequate weed control is achieved even when positioning of the vertical axis is off by several centimeters. An important feature of the weeder is a cylindrical cover that is lowered with the blade and that rests on the soil surface while the blade enters the soil. The cover ensures that the loose soil forms a mound on top of the hole. When the loose soil settles, it refills the hole.

The weeder is powered by a high-speed hydrostatic motor, which ensures that the weed and its taproot are cut into small pieces. Regrowth from small pieces of taproot is possible, yet experiments have indicated that 60%–80% of weeds destroyed in this way fail to regrow (Böhm & Finze, 2004; Böhm & Verschwele, 2004). The weeder is raised and lowered by a hydraulic cylinder. The weeder assembly can be moved laterally along a rail that is fastened to the front of the robot. The rail can be folded for transport; when extended, it allows the weeder to move laterally over a distance of 2 m.

The following method is employed to position the weeder over a weed. The robot drives at a constant speed while searching for weeds. When a weed is detected, speed is maintained until the calculated center of the weed is located exactly under the path that the weeder can follow along its rail, at which point in time the robot is stopped. Next, the weeder is moved laterally along its rail until the center of the weeder is aligned with the calculated center of the weed. Lateral movement is directed by determining a mapping from the position in the camera's field of view to the corresponding lateral position of the weeder.

2.5. Control of the Robot

Control of the robot is divided into a high-level part dealing with path following, image processing, and decisions and a low-level part for reading sensors and control of

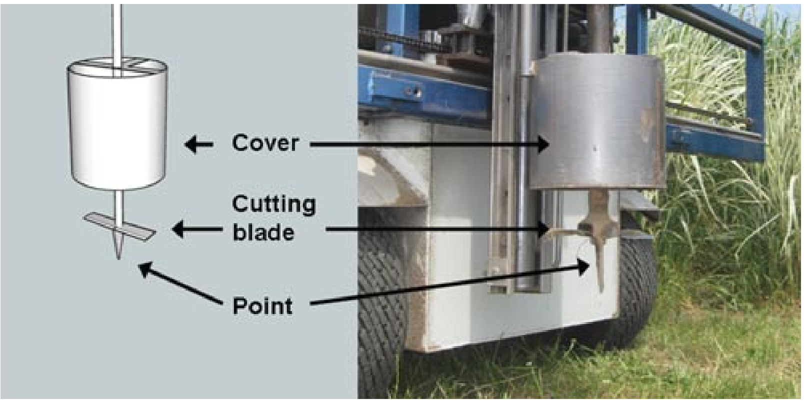

Figure 6. Diagram (left) and photo (right) of the weeder. The cover has been propped up to expose the cutting blade.

the hydraulics. The high-level part runs on a PC, and the low-level part runs on the PLC. Communication between PC and PLC is realized through a wired serial connection (EIA232E) and consists of commands sent from the PC to the PLC and of data about speed, distance traveled, and current state sent from the PLC to the PC.

At start-up, the high-level controller of the robot enters the “Idle” state. At a command from the user, it enters the “StartSeeking” state. In this state, all data structures with regard to weed detection are initialized, after which the “Seeking” state is entered. The robot accelerates until it reaches its target speed (0.5 m s^{-1}), and it captures and processes images at 2 Hz. The processing of an image takes almost 0.25 s, so when the result becomes available the robot has moved approximately 0.125 m from the position where the image was captured. Weeds are identified deterministically and tracked through successive frames through data association based on distance to the nearest neighbor. As soon as a weed is identified, its location is transmitted to the low-level control unit. The low-level control unit then enters the state “Targeting,” which has the task of making sure that the robot stops at the correct position. Whenever processing of a new frame results in an updated estimate of the location of the nearest weed, the new location is transmitted to the low-level control unit.

When the high-level-control detects that the robot has come to a stop at the location of the nearest weed (state “AtTarget”), it commands the low-level control unit to move the weeder laterally until it is positioned directly over the weed and then to activate the weeder to destroy the weed. When that action is finished, the “Seeking” state is reentered and the robot starts moving once more. Upon entering the “Seeking” state, the list of weeds in view is not deleted.

The high-level software runs on a mini-ITX PC with a Core 2 Duo (Merom) 1.66-GHz dual-core processor (Intel Corp., Santa Clara, California) and 1 GB of memory and with Windows XP (Microsoft Corp., Redmond, Washington) as the operating system. The low-level software runs on the PLC and is programmed using the CoDeSys development environment (Smart Software Solutions GmbH, Kempten, Germany). The high-level software was developed in the computer language C# and the .NET environment (Microsoft Corp., Redmond, Washington). The program uses multithreading to ensure responsiveness of critical tasks. Thus, there are separate threads to retrieve frames from the camera, to listen on the serial port, to perform the time-consuming image processing for weed detection, to log, and, finally, for the user interface.

3. EXPERIMENTAL RESULTS

The effectiveness of the robot is ultimately expressed as the reduction in weed density that results from its application. This effectiveness is affected by the functioning of the various components of the robot’s behavior. In this section we first present experimental results on key aspects of the system, namely path following, positioning of the weeder, and effectiveness of the weeder. This is followed by a presentation of the results of field experiments with the complete system.

3.1. Path Following

A number of experiments were conducted in which a path was calculated starting from the current position of the robot. Each time the path consisted of an alternation of line segments with a length of 10 m and semicircles with a radius of 2 m. In these experiments, weed detection was disabled. The robot was able to follow the path and to determine correctly the point at which one segment ended and the next one began. A typical result is given in Figure 7. Deviations from the path were on the order of decimeters on the line segments but much larger during turning. In all cases the robot was able to regain the planned path.

The observed deviations from the planned path may cause small parts of the field to be scanned twice while others are left untouched, but this does not materially

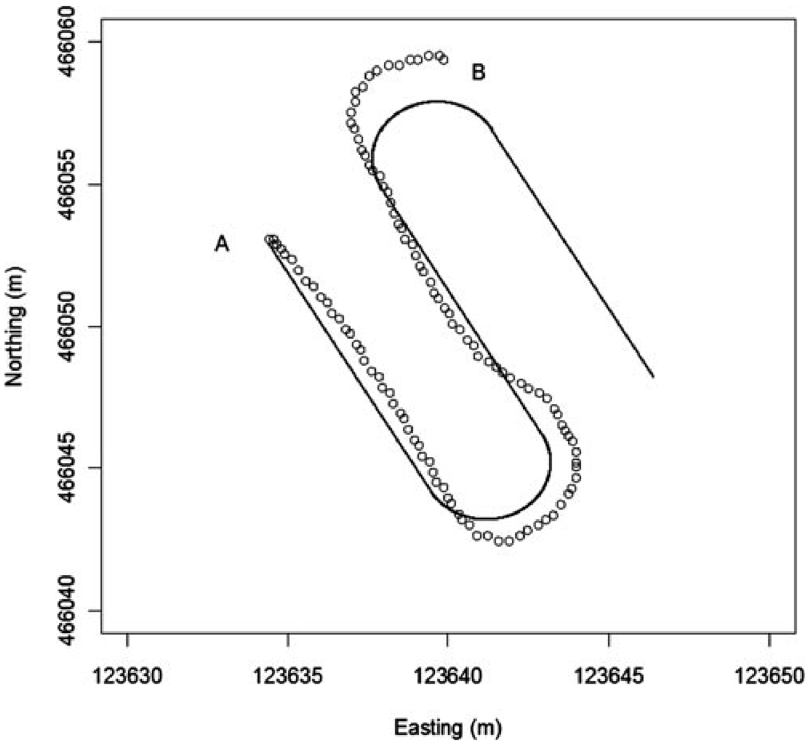

Figure 7. An experiment on path following. The planned path is indicated by the solid lines; the actual path as determined by RTK–GPS is indicated with the symbols (1-s intervals). The robot was started at A, and it was stopped at B.

affect the performance of the robot. Possible causes of the observed deviations are an insufficiently tuned PID controller, the use of skid steering, and the absence of a dynamic vehicle model.

3.2. Accuracy of Weeder Positioning

The accuracy of positioning the weeder was determined first by placing a circular piece of green cardboard (diameter 0.1 m) on grass and letting the robot find it. The green cardboard behaves similar to the leaves of broad-leaved dock when subjected to Fourier analysis, but it is easier to detect because it does not present the variation of weed leaves. The robot's speed was set to 0.5 m s^{-1}. Sudden stopping at this low speed did not result in observable sliding of the robot. Typical error between the center of the weeder and the center of the cardboard circle was <0.03 m.

The accuracy of positioning on real weeds was tested on 9 September 2008 on a dairy farm near Wilnis (52°10′55″ N, 4°55′40″ E). Twenty-seven weed plants were selected. Each time the robot was positioned at approximately 2 m from the weed, and then started. The robot was run at 0.5 m s^{-1}. The weeding action was interrupted before it destroyed the weed, and the distance from the weed's taproot to the center of the weeder was measured. This measurement combines the positioning error and the weed detection error. For the 27 measurements, the mean positioning error was 0.085 m with standard deviation 0.049 m. The time required to position and operate the weeder was determined to be approximately 12 s.

3.3. Effectiveness of Weed Control

An effectiveness of 60%–80% has been reported for the cutting weeder that we selected as our weed control method. However, these numbers were obtained with a rotational speed of approximately 1,500 rpm, whereas the speed of our weeder turned out to be limited to approximately 1,000 rpm. Therefore, we determined the effectiveness of our implementation as follows. First, on 3 October 2007, a weed was destroyed using the weeder. Flowerpots were filled with soil and weed fragments taken from the hole. The pots were put into a greenhouse and kept well watered to ensure optimal growing conditions. On 26 October 2007 the pots were examined. Many small broad-leaved docks were growing in every pot. The pots were emptied, and the small plants were washed. Unsurprisingly, some plants were regrowing from very small pieces of taproot (Figure 8).

Next, the field effectiveness of the weed control method was tested on two fields. On 5 August 2008, weeds were destroyed in a peat soil pasture on a dairy farm near

Figure 8. Regrowth of broad-leaved dock from taproot fragments. Tape measure shows sizes in centimeters.

Wilnis. On 19 September 2008 weeds were destroyed in a clay soil pasture on a dairy farm near Harlingen (53°09′54″ N, 5°28′11.51″ E). At each site, 100 solitary weeds were selected. Solitary weeds were chosen to ensure that any subsequent regrowth could not be from roots of adjacent weed plants. The weeder was manually positioned such that the center of the weeder was directly above the weed's taproot. Then the weeder was manually engaged and the weed destroyed. Each location was identified with a numbered marker. Figure 9(A) shows a location in which a weed has been controlled.

Approximately 1 month after the weeds had been controlled, the treated locations were examined. In Wilnis the locations were examined on 10 September 2008, and in Harlingen the locations were examined on 15 October 2008. At each site, it was determined in how many of the treated locations a broad-leaved dock plant was growing.

Table I. Results of two experiments on destruction of solitary plants of broad-leaved dock.

Parameter	Wilnis	Harlingen
Number of broad-leaved dock plants destroyed	100	100
Number of locations identified after 1 month	64	100
Number of locations in which regrowth of broad-leaved dock was detected	18	22
Regrowth percentage	28	22

The results are shown in Table I. The pasture in Wilnis was used for grazing after the weeds had been destroyed, and due to trampling by cattle we were unable to find some of the locations. The locations that were found showed a wide range of appearances. In some locations a small broad-leaved dock plant was growing from a piece of root [Figure 9(B)]. Some locations showed nothing but black soil. Some locations were hard to locate because adjacent grass was hanging over and growing into the location of the destroyed weed [Figure 9(C)]. In all, regrowth of broad-leaved dock was found in 24% of the cases (in 40 of 164 locations broad-leaved dock could be identified after 1 month).

3.4. Field Test of the Complete Robot

An experiment was performed to determine whether the complete robot is capable of detecting and destroying broad-leaved dock on a commercial farm with the success rate of 70% stated in the Introduction. The experiment consisted of a single treatment ("application of the robot"), which was executed twice. The experiment was conducted at the dairy farm in Wilnis mentioned earlier. This farm

Figure 9. (A) Weed immediately after cutting. (B) After 1 month, a location in which weed regrowth is visible (the small leaf in the center of the image). (C) After 1 month, a location in which weed regrowth has not occurred. Area shown is approximately 0.50 × 0.38 m.

Table II. Results of the field test of the complete robotic system over an area of 1,054 m^2.

	8 October (91 weeds)		14 October (43 weeds)		Overall (134 weeds)	
Result	No weed	Weed	No weed	Weed	No weed	Weed
Weed not detected		7		3		10
Weed detected	3	84	5	40	8	124
Successfully detected		92%		93%		93%

is located on reclaimed land with a flat topography. On 8 October 2009, and again on 14 October, a pasture was selected that presented favorable conditions for the robot. In both cases, the pasture had been allowed to regrow after a grazing period. The grass was 10–20 cm tall. Broad-leaved dock density was high and variable. The diameter of individual weed plants varied between 0.1 and 0.5 m. On both days, the weather was highly variable, rapidly changing from bright sunshine to overcast.

Large areas of the pastures were free of weeds, so the robot was repositioned a number of times into an area with weeds.

All images taken by the system were logged and used afterward to determine the number of weeds encountered, the number of false positives (weeding action in the absence of a weed), false negatives (no weeding action even though a weed is present), and the positioning error. The positioning error was determined by examining the logged images. A cross was drawn by hand at the location of the taproot as determined by a weed expert, another cross at the center of the circular area disturbed by the weeder, and the distance between the two crosses was measured. On 8 October, 91 weeds were encountered over a distance of 244 m (given an operating width of 2 m, this indicates a weed density of 2,031 plants ha^{-1}). On 14 October, 43 weeds were encountered over a distance of 283 m (759 plants ha^{-1}). In all, 93% of weeds were detected, and the false detection rate was about 6% (i.e., for every 100 weeds detected, about 6 did not represent a weed). Full results are given in Table II and Figure 10.

The pastures used for the experiment were not well maintained. Many weeds were large, grew in bunches, or had leaves that were growing in one direction from the taproot only. These weeds typically caused large errors for the localization of the taproot. On the other hand, the error for smaller weeds was typically very small. This is illustrated in Figure 11.

4. DISCUSSION

The first criterion by which the performance of the robot was judged is whether it removes 70% of the weeds, as required by the farmers. With a weed detection rate of 93% and an effectiveness of 75%, this criterion is met in the experiments reported here. The largest errors occurred with large weeds that are encountered in pasture that has not been well maintained. It follows that once a pasture is in better condition, the robot described in this paper will be able to maintain the pasture and prevent the weed from spreading.

The main objective of the work has been reached, i.e., a fully autonomous robot able to detect and destroy 70% of the weeds. Nevertheless, it is clear that several improvements can be made to the robot.

Path following accuracy is sufficient for the purpose, but could be improved. On the basis of available data, it is not possible to determine whether the skid steering, the absence of a dynamic vehicle model, or a combination of these factors is responsible for the relatively poor accuracy. The robot was designed for and tested in a country where pastures are overwhelmingly flat. We have no information about how the path following algorithm will function in an alpine environment.

The choice of a hydraulic power system has had two consequences. The most serious is that the rotational speed

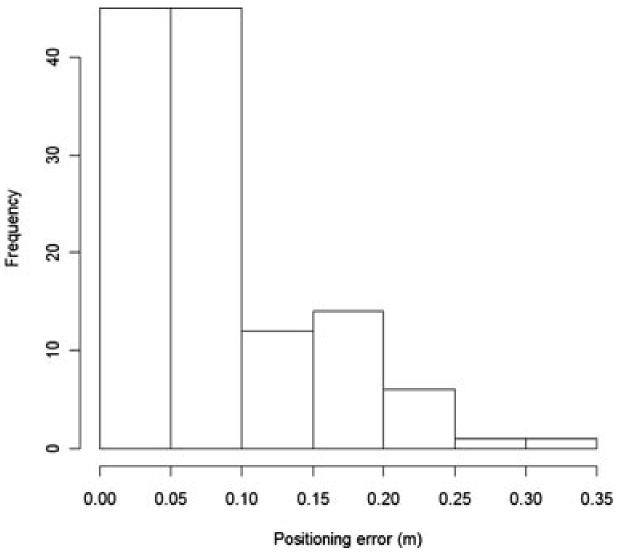

Figure 10. Histogram of the positioning error of the weeder. Shown are the results for 124 weed control actions.

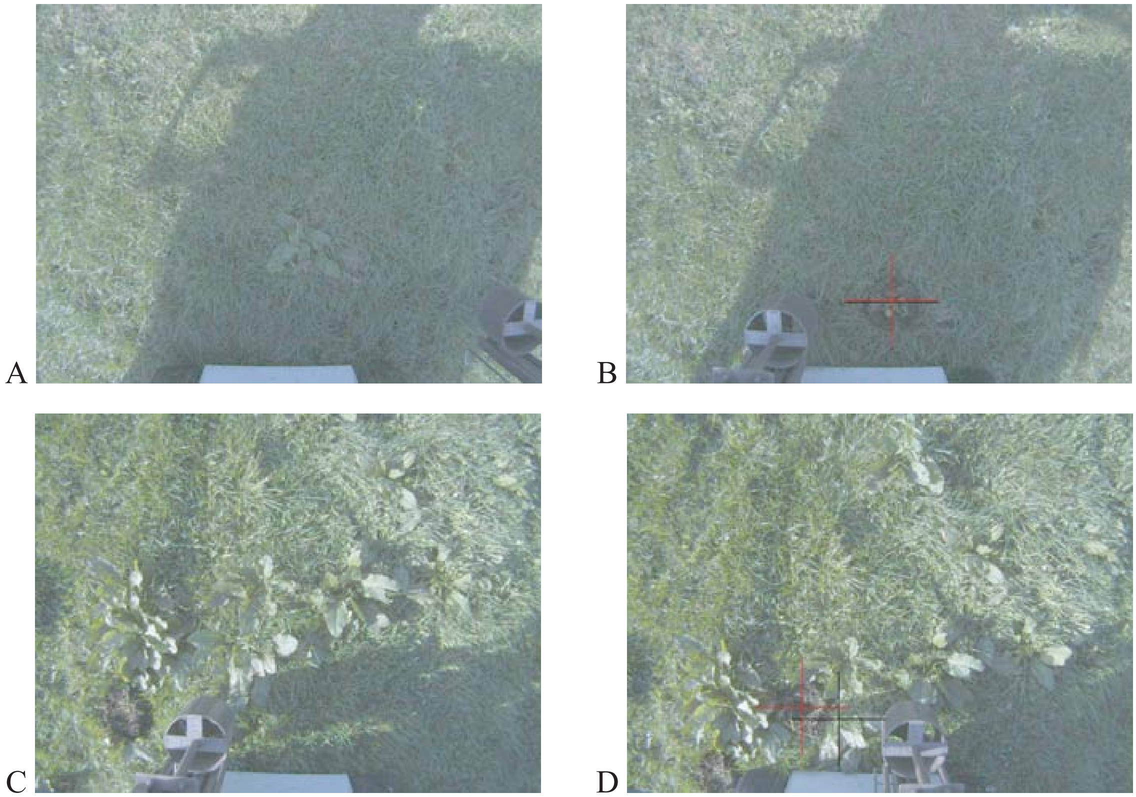

Figure 11. Two examples of a weed before and after cutting, as viewed by the camera used for weed detection: (A) a well-defined weed can be seen; (B) the weed has been controlled, and the positioning error is estimated at 0.01 m; (C) the robot encounters a patch of weeds growing bunched together; and (D) the weeder has been engaged; the distance from the center of the disturbed area to the center of the nearest weed is estimated at 0.22 m.

of the weeder does not exceed 1,000 rpm, which may result in less than complete destruction of the weed and lead to a higher-than-desired regrowth rate. The other consequence is the relatively high cost of the power distribution system. An electrical power system might be used to address both these problems.

The robot uses ambient light for image acquisition. Application of the algorithm of Marchant et al. (2004) strongly reduces the effect of changes in illumination but does not completely remove it. However, the texture features upon which the weed detection is based are remarkably constant; any effect that remains after application of Marchant's algorithm is taken into account by changing the value of a single parameter (the threshold, i.e., step 3 in Figure 5). The data presented in this paper were collected with only one value for this parameter. We did not test the robot when the grass was wet from dew or rain, because specular reflection from wet leaves may be expected to influence weed detection.

The paragraphs above point to straightforward ways in which the robot could be improved: add steering wheels, use electric power, and add lighting (and shield ambient light). But this does not detract from the fact that the current implementation of the robot, once it has been parameterized for prevalent light conditions, is an effective tool to reduce the density of broad-leaved dock.

In Section 1, several challenges were mentioned that are relevant to the introduction of robots into agriculture. The following paragraphs summarize how these challenges have been met in the case of the current robot.

A major scientific challenge involved detection of broad-leaved dock. The vision-based method of Van Evert et al. (2009) was used to detect broad-leaved dock, and it was found that this method gives acceptable results in field conditions. The method works best in short, untrampled grass and when broad-leaved dock is growing in rosette form. These conditions typically occur 1–3 weeks after the grass has been cut, indicating that this would be the preferred time to use the robot. When several plants are growing in close proximity, our algorithm may detect them as one plant. This weakness must be addressed in further work. There is also scope to refine the weed detection method by using wavelets (Mallat, 1999; Schut & Ketelaars, 2003) or by combining vision with a range camera (Holpp et al., 2008).

The required accuracy of the robot is not high. Interviews with a focus group of farmers revealed that robot performance would be considered satisfactory if at least 70% of the weeds were destroyed. The attitude to false positives (detection of a weed where there isn't one) was similarly relaxed: it was observed that the hooves of a cow may cause as much damage to the grass as a robot that punches an unnecessary hole.

Successful removal of a weed requires, first, that it is detected, and second, that it does not grow back after having been destroyed. With respect to the latter, we intend to add to the robot a mechanism to sow grass seed at each location where a weed has been destroyed. Grass growing from the seed will compete with broad-leaved dock plants and reduce the survival rate of the weed.

We were able to reduce navigation requirements to a simple path following problem because in grass the robot can drive anywhere. Obstacle avoidance has not yet been implemented but can be addressed through distance sensors.

Performing any kind of physical actuation in or close to the soil places heavy demands on the actuator. Fortunately, for the task of controlling broad-leaved dock, the design of a simple and robust instrument was available.

Safety is a concern with heavy, powerful, autonomous equipment. The robot will be used mostly in polders—reclaimed land where pastures are separated from the road by water-filled drainage ditches. This reduces the risk of the robot escaping from the field and addresses one of the most serious safety concerns.

The introduction of a robot into a farm has the best chance of being successful if the robot provides a clear benefit to the farmer. Most organic farmers have virtually no spare time to devote to broad-leaved dock removal, so our robot will easily increase the number of weeds removed from the farm. This robot will provide a benefit even if it works slowly. This is a situation much different from weeding in a row crop where there is a short time window to get the work done and a robot may have to outperform a tractor driven at 7 km h^{-1}. It is also different from cucumber harvesting, where the robot needs to be faster than human pickers (Van Henten, Van Tuijl, Hemming, Kornet, Bontsema, et al., 2003).

The operating width of the robot is 2 m. At a speed of 0.5 m s^{-1}, the robot's work rate is 1 m^2 s^{-1}, which means that traversing 1 hectare would take on the order of 3 h. The amount of time required for destruction of weeds depends on the number of weeds per hectare. If we assume a moderate density of 1,000 weeds ha^{-1}, removing them (at 10–12 s $plant^{-1}$) would require approximately 4 h. An indicative number for the work rate of the robot is thus 7 h ha^{-1}. Given that a typical dairy farm in The Netherlands is between 50 and 100 hectares, that not all land is infested with broad-leaved dock, that the weed need be controlled only once a year, and that the robot could work from May until October, it follows that several farms could share the use of one robot.

Although it is difficult to provide a reliable cost estimate for a commercial version of our robot, project expenditure indicates that a price of approximately €50,000 (~$65,000) is possible (but this may possibly be reduced by moving away from hydraulic power—see above). This number is slightly lower than the one mentioned by Pedersen et al. (2006), in part because the price of a GPS receiver is now lower. Depreciation, maintenance, and operating cost are estimated at €10,000 per year, about half the number mentioned by Pedersen et al. (2006), in part because the cost of the RTK–GPS correction signal is now lower and in part because our robot does not use herbicides. If the robot is used on five farms, this leaves an annual cost of €2,000 per farm. The farmers in our study group have indicated that this cost is acceptable.

Apart from its usefulness in organic agriculture, there may be scope for development of a version of the robot that uses a herbicide to control the weeds. Using a herbicide would make it possible to construct a robot that is lighter, cheaper, and inherently safer than the one described in this paper. If we assume that such a robot would treat each detected weed individually by applying herbicide to a circle with a diameter of 0.2 m and assume a density of 1,000 weeds ha^{-1}, use of such a robot would result in a reduction in herbicide use in excess of 99% relative to treatment of the whole field. The marketing potential of such a robot would be larger because it may appeal to conventional dairy farmers (95% of Dutch dairy farmers). Conventional dairy farmers currently have little incentive to reduce pesticide use, but this may change as society places ever greater value on the prevention of contamination of water sources (Kempenaar, Lotz, van der Horst, Beltman, Leemnans, et al., 2007; Kropff, Bastiaans, Kempenaar, & Van der Weide, 2008).

5. CONCLUSION

A prototype robot was developed that can navigate a pasture, detect broad-leaved dock, and remove any weeds found. Experiments indicate that navigation by means of path following is sufficiently precise for the task, that 93% of broad-leaved dock plants are detected, and that 75% of controlled weeds do not regrow. The preset goal of destruction of 70% of the weed plants was met.

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REFERENCES

Åstrand, B., & Baerveldt, A. J. (2003). A mobile robot for mechanical weed control. International Sugar Journal, 105(1250), 89–95.

Bakker, T., Van Asselt, C. J., Bontsema, J., Müller, J., & Van Straten, G. (2006, September). Autonomous navigation with a weeding robot. Proceedings of the Automation Technology for Off-Road Equipment Conference 2006, Bonn, Germany (pp. 51–57).

Bakker, T., Wouters, H., van Asselt, K., Bontsema, J., Tang, L., Müller, J., & van Straten, G. (2008). A vision based row detection system for sugar beet. Computers and Electronics in Agriculture, 60(1), 87–95.

Billingsley, J., Visala, A., & Dunn, M. (2008). Robotics in agriculture and forestry. In B. Siciliano & O. Khatib (Eds.), Springer handbook of robotics (pp. 1065–1077). Berlin: Springer.

Blackmore, B. S., Stout, W., Wang, M., & Runov, B. (2005). Robotic agriculture—The future of agricultural mechanisation? In J. V. Stafford (Ed.), Precision Agriculture '05 (pp. 621–628). Wageningen, The Netherlands: Wageningen Academic Publishers.

Bleeker, P., Van der Schans, D. A., & Van der Weide, R. Y. (2007, March). New ways of sowing or planting onions for innovative intrarow weeders Proceedings 2007 7th EWRS Workshop on Physical Weed Control, Salem, Germany (pp. 103–104).

Böhm, H., & Finze, J. (2004). Überprüfung der Effektivität der maschinellen Ampferregulierung im Grünland mittels WUZI unter differenzierten Standortbedingungen. [Testing the effectiveness of mechanical control of docks in grassland with the WUZI under a variety of conditions.] Available online at http://orgprints.org/4165/01/B%C3%B6hm-B%C3%96L-Pflschutz-2004.pdf. Verified 15 April 2008.

Böhm, H., & Verschwele, A. (2004). Ampfer- und Distelbekämpfung im Ökologischen Landbau. [Control of docks and thistles in organic agriculture.] In G. Rahmann & S. Kühne (Eds.), Ressortforschung für den Ökologischen Landbau (vol. 273, pp. 39–48). Braunschweig, Germany: Bundesforschungsanstalt für Landwirtschaft (FAL).

Bond, W., Davies, G., & Turner, R. W. (2007). The biology and non-chemical control of broad-leaved dock (*Rumex obtusifolius* L.) and curled dock (*R. crispus* L.). Available online at http://organicgardening.org.uk/organicweeds/downloads/dock%20review.pdf. Verified 23 September 2008. Retrieved September 22, 2008.

Bonicelli, B., & Monod, M. O. (1987). A self-propelled plowing robot. ASAE Paper No. 87-1064. St. Joseph, MI: ASAE. Available at http://agris.fao.org/agris-search/search/display.do?f=1989/US/US89135.xml;US8853760.

Cavers, P. B., & Harper, J. L. (1964). *Rumex obtusifolius* L. and *R. crispus* L. Journal of Ecology, 52(3), 737–766.

Courtney, A. D. (1985). The role and importance of docks in grassland. Agriculture in Northern Ireland, 59, 388–392.

Dürr, L., Anken, T., Bollhalder, H., Sauter, J., Burri, K.-G., & Kuhn, D. (2004). Machine vision detection and microwave based elimination of *Rumex obtusifolius* L. on grassland. Available online at http://www.aramis.admin.ch/Dokument.aspx?DocumentID=629. Last accessed October 12, 2010.

Finze, J., & Böhm, H. (2004). Effect of direct control measures and grazing management on the density of dock species (*Rumex* spp.) in organically managed grassland. Zeitschrift fur Pflanzenkrankheiten und Pflanzenschutz—Journal of Plant Diseases and Protection, Special Issue XIX, 527–535.

Foglia, M. M., & Reina, G. (2006). Agricultural robot radicchio harvesting. Journal of Field Robotics, 23(6–7), 363–377.

Gebhardt, S., & Kühbauch, W. (2007). A new algorithm for automatic *Rumex obtusifolius* detection in digital images using colour and texture features and the influence of image resolution. Precision Agriculture, 8(1–2), 1–13.

Gebhardt, S., Schellberg, J., Lock, R., & Kühbauch, W. (2006). Identification of broad-leaved dock (*Rumex obtusifolius* L.) on grassland by means of digital image processing. Precision Agriculture, 7(3), 165–178.

Hague, T., & Tillett, N. D. (1996). Navigation and control of an autonomous horticultural robot. Mechatronics, 6(2), 165–180.

Holpp, M., Anken, T., Šeatović, D., Grüninger, R., & Hüppi, R. (2008, July). 3D object recognition, localization, and treatment of *Rumex obtusifolius* in its natural environment. Proceedings of the 9th International Conference on Precision Agriculture, Denver, CO.

Ishak, A. J., Hussain, A., & Mustafa, M. M. (2009). Weed image classification using Gabor wavelet and gradient field distribution. Computers and Electronics in Agriculture, 66(1), 53–61.

Kempenaar, C., Lotz, L. A. P., van der Horst, C. L. M., Beltman, W. H. J., Leemnans, K. J. M., & Bannink, A. D. (2007). Trade off between costs and environmental effects of weed control on pavements. Crop Protection, 26(3), 430–435.

Kropff, M. J., Bastiaans, L., Kempenaar, C., & Van der Weide, R. Y. (2008). The changing role of agriculture and tomorrow's weed research agenda. Journal of Plant Diseases and Protection—Zeitschrift für Pflanzenkrankheiten und Pflanzenschutz, Special Issue XXI, 3–8.

Latsch, R., Sauter, J., Hermle, S., Durr, L., & Anken, T. (1999). Control of *Rumex obtusifolius* L. in grassland using microwave technology. VDI-Berichte, 2001, 501–506.

Mallat, S. (1999). A wavelet tour of signal processing (2nd ed.). San Diego, CA: Academic Press.

Marchant, J. A., Tillett, N. D., & Onyango, C. M. (2004). Dealing with color changes caused by natural illumination in outdoor machine vision. Cybernetics and Systems, 35(1), 19–33.

Niggli, U., Nosberger, J., & Lehmann, J. (1993). Effects of nitrogen-fertilization and cutting frequency on the competitive ability and the regrowth capacity of *Rumex obtusifolius* L. in several grass swards. Weed Research, 33(2), 131–137.

Oswald, A. K., & Haggar, R. J. (1983). The effects of *Rumex obtusifolius* on the seasonal yield of 2 mainly perennial ryegrass swards. Grass and Forage Science, 38(3), 187–191.

Pedersen, S. M., Fountas, S., Have, H., & Blackmore, B. S. (2006). Agricultural robots—System analysis and economic feasibility. Precision Agriculture, 7(4), 295–308.

Polder, G., Van Evert, F. K., Lamaker, A., De Jong, A., Van der Heijden, G. W. A. M., Lotz, L. A. P., Van der Zalm, T., & Kampenaar, C. (2007, July). Weed detection using textural image analysis. Paper presented at the 6th Biennial Conference of the European Federation of IT in Agriculture (EFITA), Glasgow, UK. Available online at http://edepot.wur.nl/28203. Accessed October 12, 2010.

Reid, J. F., Zhang, Q., Noguchi, N., & Dickson, M. (2000). Agricultural automatic guidance research in North America. Computers and Electronics in Agriculture, 25(1–2), 155–167.

Rombouts, N. J. L., & Rombouts, P. K. M. (2002). Netherlands Patent No. 1017794.

Schut, A. G. T., & Ketelaars, J. (2003). Imaging spectroscopy for early detection of nitrogen deficiency in grass swards. Njas-Wageningen Journal of Life Sciences, 51(3), 297–317.

Šeatović, D. (2008, June). 3D object recognition, localization, and treatment of *Rumex obtusifolius* in its natural environment. Paper presented at the Proceedings of the 1st International Conference on Machine Control & Guidance, Zurich, Switzerland. Available online at http://www.mcg.ethz.ch/papres/Seatovic_17.pdf. Accessed October 12, 2010.

Šeatović, D., Kutterer, H., Anken, T., & Holpp, M. (2009). Automatic weed detection in grassland. VDI-Berichte, 2060, 187–192.

Slaughter, D. C., Giles, D. K., & Downey, D. (2008). Autonomous robotic weed control systems: A review. Computers and Electronics in Agriculture, 61(1), 63–78.

Sorensen, 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.

Strang van Hees, G. (2006). Globale en lokale geodetische systemen [Global and local geodetic systems] (vol. 30). Delft, The Netherlands: Nederlandse Commissie voor Geodesie [Dutch Geodetical Commission].

Tang, L., Tian, L., & Steward, B. L. (2003). Classification of broadleaf and grass weeds using Gabor wavelets and an artificial neural network. Transactions of the ASAE, 46(4), 1247–1254.

Thoma. (2005). Dit is Automaatje [This is the "Automaatje" robot]. Retrieved July 20, 2008, from http://www.joz.nl/brochures/files/JOZ0005_def.pdf#search=%22thoma%20automaatje%22.

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.

Tillett, N. D., Hague, T., & Marchant, J. A. (1998). A robotic system for plant-scale husbandry. Journal of Agricultural Engineering Research, 69, 169–178.

Van Eekeren, N., & Jansonius, P. J. (2005). Ridderzuring beheersen. Stand van zaken in onderzoek en praktijk. [Control of broad-leaved dock. State of the art in research and practice.] Driebergen, The Netherlands: Louis Bolk Instituut.

Van Evert, F. K., Polder, G., Van der Heijden, G. W. A. M., Kempenaar, C., & Lotz, L. A. P. (2009). Real-time, vision-based detection of *Rumex obtusifolius* L. in grassland. Weed Research, 49(2), 164–174.

Van Evert, F. K., Van der Heijden, G. W. A. M., Lotz, L. A. P., Polder, G., Lamaker, A., De Jong, A., Kuyper, M. C., Groendijk, E. J. K., Neeteson, J. J., & Van der Zalm, T. (2006). A mobile field robot with vision-based detection of volunteer potato plants in a corn crop. Weed Technology, 20(4), 853–861.

Van Henten, E. J., Van Tuijl, B. A. J., Hemming, J., Kornet, J. G., Bontsema, J., & Van Os, E. A. (2003). Field test of an autonomous cucumber picking robot. Biosystems Engineering, 86(3), 305–313.

Van Middelkoop, J., De Visser, M., & Schilder, H. (2005). Beheersing van ridderzuring op biologisch grasland in het project Bioveem. [Control of broad-leaved dock in organic grassland in the "Bioveem" project.] Animal Sciences Group Report 14. Lelystad, The Netherlands: Animal Sciences Group.

Van Zuydam, R. P., & Achten, V. T. J. M. (2002). Autonoom voertuig vult ontbrekende arbeidskracht aan. [An autonomous vehicle to compensate a shortage of labor.] Landbouwmechanisatie, 53(1), 22–23.