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Robotic control of broad-leaved dock

F.K. van Evert[1], J. Samsom[2], G. Polder[1], M. Vijn[3], H.-J. van Dooren[4], E.J.J. Lamaker[5], G.W.A.M. van der Heijden[1], C. Kempenaar[1], A.J.A. van der Zalm[1], L.A.P. Lotz[1]
[1]Plant Research International, PO Box 16, 6700 AA Wageningen, The Netherlands.
[2]Gagelweg 1, 3648 AV Wilnis, The Netherlands.
[3]LaMi, PO Box 80300, 3508 TH Utrecht (current address: Applied Plant Research, P.O. Box 167, 6700 AD Wageningen, The Netherlands).
[4]Animal Sciences Group, PO Box 65, 8200 AB Lelystad, The Netherlands.
[5]Wageningen University and Research Centre, Wageningen, The Netherlands (current address: MARIN, P.O. Box 28, 6700 AA Wageningen, The Netherlands).
Corresponding author: frits.vanevert@wur.nl.

Abstract
Broad-leaved dock (*Rumex obtusifolius* L.) is a common and troublesome grassland weed with a wide geographic distribution. In organic farming, the best option to control the weed is manual removal of the plants. In this report we describe the development and first tests of a robot to detect and control broad-leaved dock. An analysis of requirements led to the construction of a diesel-powered frame of 1.25 x 1.11 m to which four independently driven wheels are attached. Weeds are detected with a downward-looking camera that provides full-colour images with a resolution of 1.5 mm per pixel. Image processing is based on Fourier analysis of sub-images (tiles) of 8x8 pixels. Weeds are controlled using the method proposed by Austrian farmer F. Riesenhuber. This method consists of a chopper with a single 0.20 m blade that rotates around a vertical axis at 1500 rpm and is pushed into the ground at the location of the weed. In field tests the robot was run at 0.5 m/s. Under favourable conditions, more than 90% of weeds were detected and positioning of the chopper occurred with adequate precision. The time required to position and operate the chopper was determined to be 12 s. Approx. 25% of controlled weeds exhibited regrowth. We conclude that our robot provides an attractive alternative to manual removal of broad-leaved dock.
Keywords: *Rumex obtusifolius* L., organic farming, machine vision

Introduction

Broad-leaved dock (*Rumex obtusifolius* L.) is a common and troublesome weed with a wide geographic distribution (Cavers and Harper, 1964). If broad-leaved dock is not controlled, it will reach a high population density and reduce grass yield by 10 to 40% (Courtney, 1985). The weed is readily consumed by livestock but its nutritive value is less than that of grass (Oswald and 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.
In conventional farming, the weed is normally controlled by using the selective herbicide MCPA (2-methyl-4-chlorophenoxyacetic acid). In organic farming no pesticides are used and broad-leaved dock must 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 hundreds of hours per year on a single farm (Edith Finke, agricultural advisor, DLV, personal communication). Frequent cutting alone is insufficient to prevent broad-leaved dock from spreading (Niggli *et al.*, 1993). A review of non-chemical means to control broad-leaved dock is given by Bond *et al.* (2007).
Robots have been proposed by many workers to reduce the cost and increase the focus of agricultural operations (e.g. Blackmore *et al.*, 2005). Automatic detection of broad-leaved dock has been studied by Šeatović (2008), Holpp *et al.* (2008), Gebhardt & Kühbauch (2007), Gebhardt *et al.* (2006), and Dürr *et al.* (2004). Various methods to control broad-

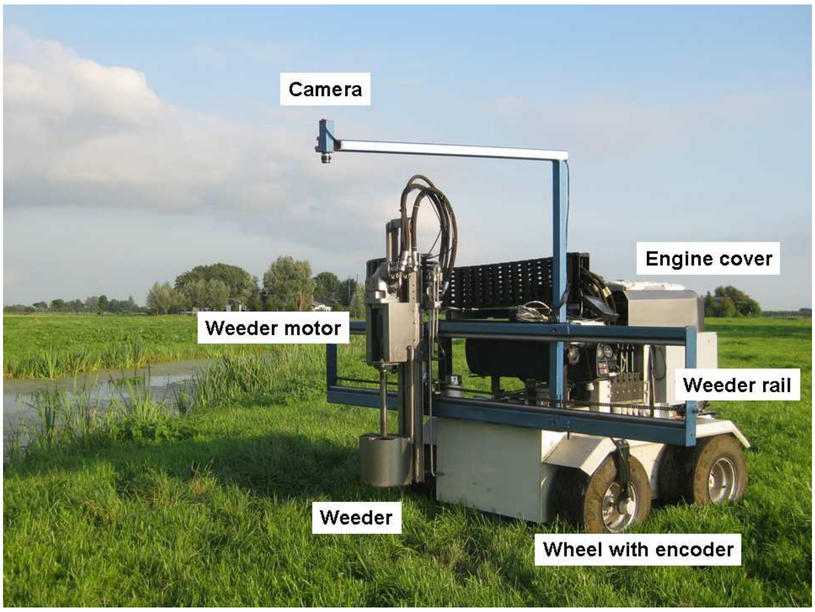


Figure 1. Robot to detect and control broad-leaved dock. The GPS antenna is not shown, but has been mounted near the camera.

leaved dock have been suggested: mechanical destruction (Böhm and Finze, 2004; Finze and Böhm, 2004), microwaves (Dürr *et al.*, 2004; Latsch *et al.*, 1999), and cultural measures (Van Middelkoop *et al.*, 2005). Navigation on agricultural fields has been studied by Bakker *et al.* (2006), Vougioukas *et al.* (2006), and Reid *et al.* (2000), among others.
The objective of this paper is to describe a robot to detect and control broad-leaved dock. We address the current state of the project as well as the elements of the project that contributed to its success.

Design and construction of the robot, and preliminary experiments
Conversations with farmers indicated that a robot would be deemed useful if it can remove 70% of broad-leaved dock plants. We based our method of weed removal on that of Riesenhuber (Böhm and Finze, 2004; Van Eekeren and Jansonius, 2005). It has been reported that with this method 20-40% of removed weeds exhibit regrowth (Finze and Böhm, 2004), thus this method seems acceptable. The Riesenhuber method requires a robot which has a fairly large power source and the mass of the robot needs to be sufficiently large to be able to push the weeder into the ground. Broad-leaved dock often occurs in patches, whereas a pasture may contain patches as well as individual plants. Thus, the robot will have to search the entire pasture. Pastures are typically free of obstacles and tight manoeuvring is not required. The robot will have to be capable of many hours of continuous operation and must thus carry a large energy store. The work rate is not critical, because weeds can be detected and controlled from late April to October.
The above considerations led to the design presented in Fig. 1. The robot's base consists of a rigid frame of 1.25 x 1.11 m to which four independently driven wheels are attached. We implemented skid steering in order to keep construction light and to keep costs down. Power is provided by a 36 kW Kubota (Kubota Corp., Osaka, Japan) diesel engine.
A schema of the main components of the robot is given in Fig. 2. Hydraulics are controlled by a six-fold proportional valve block connected to a Programmable Logic Controller (PLC; Ecomat 100, IFM Electronics GmbH, Essen, Germany). The PLC receives inputs from incremental encoders mounted on the front wheels, from a remote control receiver, and from the PC that provides overall control of the system. The wheel encoders are used to regulate the robot's driving speed. The encoder counts are input to separate PID controllers for the left

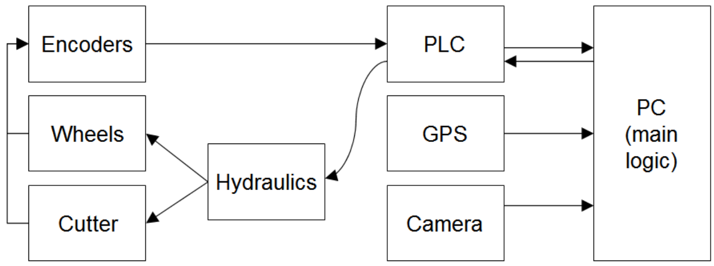


Figure 2. The main components of the robot and their interactions. Arrows denote flow of information or control.

and right wheels. The PC provides overall control of the system and functions as a pre-processor of the signals from the GPS receiver and the vision system.

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 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 approx. 1.2 x 0.9 m. Images are taken at 2 fps with a resolution of 1600 x 1200 pixels, resulting in a resolution of approx. 1.5 mm on the ground per pixel.

Path following

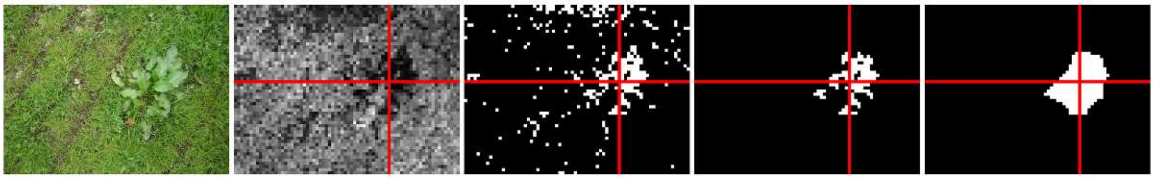
For the purpose of detecting and removing broad-leaved dock in a pasture, it is sufficient that the robot follows a pre-defined path; autonomous path planning is not required. We use a dual-frequency GPS/GLONASS receiver (AsteRx2, Septentrio, Leuven, Belgium) to determine the robot's position. RTK precision is obtained by using correction signals from a commercial network of base stations. Path following is achieved using a PID controller.

Weed detection

Broad-leaved dock plants are detected using machine vision with a method developed earlier (Polder *et al.*, 2007; Van Evert *et al.*, 2009). The method is based on the observation that grass leaves are long and narrow (several mm), whereas the leaves of broad-leaved dock are at least an order of magnitude wider. Consequently, an image with grass contains more color and intensity transitions than an image with broad-leaved weed (Fig. 3). Van Evert *et al.* (2009) reported that they were able to detect 89% of weeds in their data set.

As the robot moves towards a weed, that weed will typically appear in several successive frames. Also, more than one weed may appear in a single frame. Weeds are tracked from frame to frame through nearest-neighbour matching; the robot's speed is taken into account.

We have conducted preliminary tests to determine the accuracy of weed detection by taking the robot to a number of different pastures and observing its performance. Detection works well when broad-leaved dock plants are solitary and their growth form is a well-defined rosette; when ambient light is stable over time; and when the grass in which the weeds grow is short and untrampled. Broad-leaved dock is very variable in appearance. In early growth, it consists of a tight bunch of leaves with the taproot located in the center. In later growth, it may consist of two or more leaves on long stems, which appear to the algorithm as separate plants. When the grass is long, its leaves fall on top of each other and the texture becomes similar to that of broad-leaved dock; similarly, an image of trampled grass does not show the color transitions on which the weed detection algorithm is based. The effect of shadows is removed adequately with the algorithm of (Marchant *et al.*, 2004).



A B C D E

Figure 3. Image processing to detect broad-leaved dock. A color image (A; 1.2 m x 0.9 m) is taken with a downward-looking camera. The resolution of this image is 1.5 mm per pixel. Shadows are removed by transforming to a monochrome image using the method of Marchant *et al.* (2004). The resulting image is divided into sub-images (tiles) of 8x8 pixels and each tile is subjected to two-dimensional Fourier analysis. The power of the Fourier spectrum for all spatial frequencies above zero is a measure for the probability that the image tile shows a weed (Van Evert *et al.*, 2009). Following Fourier analysis (B), a threshold is applied to identify the pixels which likely lie on a weed (C). Weed-pixels that are not close to other weed-pixels are removed from the image (D). Then, clusters of adjacent weed-pixels are joined through a morphological closing operation; any remaining object is considered to represent a weed (E). The centroid of each object is taken as the location of the taproot of the detected weed.

Weed control

We based weed control on the vertical rod weeder proposed by Austrian farmer F. Riesenhuber and which was described and evaluated by Finze & Böhm (2004). Our implementation consists of a single 0.20 m blade that rotates around a vertical axis and is pushed into the ground at the location of the weed. The size of the blade ensures that adequate weed control is achieved even when positioning is off by several cm.

An important feature of the weeder is the cylindrical cover which keeps the soil that is dug up in 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 capable of rotating at 1500 rpm. At this speed, 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 and Finze, 2004; Böhm and Verschwele, 2004). The weeder is raised and lowered by a hydraulic cylinder. The weeder assembly can be moved along a rail that is fastened to the front of the vehicle. 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's speed is instantly reduced to 0. 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.

The accuracy of positioning on real weeds was tested on 9 September 2008, on a dairy farm near Wilnis. We selected 27 weeds. We positioned the robot at approximately 2 m from each weed and then started it. The robot was run at 0.5 m/s. We interrupted the weeding action before it destroyed the weed and measured the distance from the weed's taproot to the center of the weeder. This measurement combines the positioning error and the weed detection error. For the 27 measurents, the mean error was 0.085 m with standard deviation 0.049 m; full results are shown in Fig. 4.

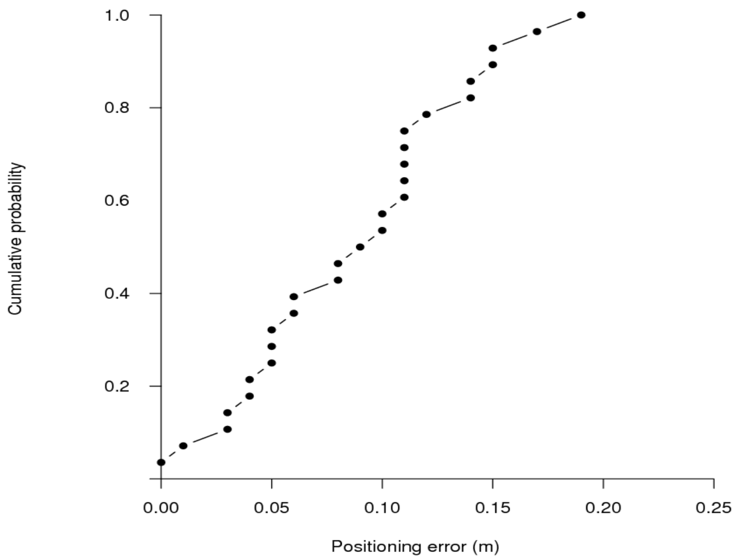


Figure 4. Cumulative probability of the error in locating the taproot of broad-leaved dock plants. The error is defined as the distance (m) between the center of the weeder and the human-determined position of the taproot, measured experimentally with the robot described in this paper, and is due to a combination of the algorithm and the mechanical positioning of the robot and the weeder.

The time required to position and operate the weeder was determined to be approx. 12 s. Field effectiveness of the weed control method was tested on two sites. On 5 August 2008, weeds were destroyed in a peat soil pasture on a dairy farm near Wilnis. On 19 September 2008 weeds were destroyed in a clay soil pasture on a dairy farm near Harlingen. 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. Approximately one month after the weeds had been controlled, the locations were examined. In Wilnis the locations were examined on 10 September 2008, in Harlingen the locations were examined on 15 October 2008. At each site, we determined the number of locations in which a broad-leaved dock plant was growing.

The pasture in Wilnis was used for grazing after the weeds had been controlled and due to trampling by cattle we were only able to find 64 of the 100 locations. Overall, we found regrowth of broad-leaved dock in 40 out of 164 (24%) locations after one month. The locations ranged in appearance from black soil to overgrown with grass. In a few locations a small broad-leaved dock plant could clearly be seen regrowing from a piece of root. Because we did not want to disturb the locations, we could in most cases not determine whether a weed was growing from seed or regrowing from a piece of root.

Control

Control of the robot is divided in a high-level part dealing with path following, image processing and decisions, and a low-level part for reading sensors and control of the hydraulics. The high-level part runs on a PC, while the low-level part runs on the PLC. Communication between PC and PLC is realized through a wired serial connection 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.

Discussion

The major scientific challenge involved detection of broad-leaved dock. Fortunately, this is a relatively straight-forward problem because of the clear textural contrast between broad-leaved dock and grass. We used the vision-based method of Van Evert, *et al.* (2009). 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 this 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 and Ketelaars, 2003) or by combining vision with a range camera (Holpp *et al.*, 2008).

Required accuracy of the robot is not high. Interviews with the study group farmers revealed that robot performance would be considered satisfactory even if no more than 70% of the weeds were destroyed. The attitude to false-positives (detection of a weed where there isn't one) was similarly relaxed: a playful cow also causes in a playful mood 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 doesn't grow back after having been destroyed. 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.

The technical demands placed on our actuator could be met. The design of a simple instrument was available. Safety is a concern with 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.

Currently the operating width of our robot is 1.2 m, but this will be increased to 2 m by replacing the current lens with a lens with a larger opening angle. Then, at a speed of 0.5 m/s, the robot's work rate will be 1 m^2/s, which means that traversing one hectare would take on the order of 3 hours. The amount of time required for destruction of weeds depends on the number of weeds per hectare. If we assume a moderate density of 1000 weeds/hectare, removing these (at 10-12 s per plant) would require approximately 4 hours. An indicative number for the work rate of the robot is thus 7 hours/hectare. Given that a typical dairy farm in The Netherlands is between 50 and 100 hectare, 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.

The introduction of robotics into farming holds great promise in terms of cost reduction, increased focus and reducing the dependency on the availability of labor. Nevertheless, even an innovation that provides a clear benefit may fail to be adopted (Rogers, 1995), possibly because it provides a service that is not in demand (Jorgensen *et al.*, 2008). A recommendation to avoid adoption failure of a new technology is to form a coalition of key actors with converging interest who are willing to pool their resources to achieve a common goal (Cramb, 2000). Indeed, this is how the work described here has proceeded. The work was started after a representative of a study group of organic dairy farmers approached researchers of Wageningen UR in 2005. The members of the study group had unanimously identified broad-leaved dock as the most immediate problem in the operation of their farms. The study group identified stakeholders and approached them for funding, in addition to the funds they were able to invest themselves. Thus, from the start, the project was wellembedded with the farmers who will eventually use the robot.

Conclusion

We have developed a prototype robot to detect and control broad-leaved dock in grass. First experiments on aspects of the system indicate that navigation by means of path following, detection of broad-leaved dock, and control of broad-leaved dock all work satisfactorily. Detection of broad-leaved dock works best when the grass is short and untrampled and when the weeds are growing in rosette form. Further work is needed to improve detection of the weed and to determine performance of the whole system under a variety of conditions.

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