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Robotic in-row weed control in vegetables

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A R T I C L E I N F O

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A B S T R A C T

Vegetables and other row-crops represent a large share of the agricultural production. There is a large variation in crop species, and a limited availability in specialized herbicides. The robot presented here utilizes systematic growing techniques to navigate and operate in the field. By the use of machine vision it separates seeded vegetable crops from weed. Each weed within the row is treated with individual herbicide droplets, without affecting the crop. This results in a significant reduction in herbicide use, and allows for the use of herbicides that would otherwise harm the crop.

The robot is tailored to this purpose with cost, maintainability, efficient operation and robustness in mind. The three-wheeled design is unconventional, and the design maintains maneuverability and stability with the benefit of reduced weight, complexity and cost.

Indoor pot trials with four weed species demonstrated that the Drop-on-Demand system (DoD) could control the weeds with as little as 7.6 µg glyphosate or 0.15 µg iodosulfuron per plant. The results also highlight the importance of liquid characteristics for droplet stability and leaf retention properties. The common herbicide glyphosate had no effect unless mixed with suitable additives. A field trial with the robot was performed in a carrot field, and all the weeds were effectively controlled with the DoD system applying 5.3 µg of glyphosate per droplet. The robot and DoD system represent a paradigm shift to the environmental impact and health risks of weed control, while providing a valuable tool to the producers.

1. Introduction

The production of row crops represent a significant portion of the overall food production in the world. This production is composed of large variety of crops of which each individual crop has a smaller volume. In contrast to major crops such as corn, soy and cereal, the vegetable crops have a smaller selection of available herbicides. In the past 20 years we have seen a significant increase in herbicide resistant weeds (Heap, 2014), while the availability of herbicides has been reduced by regulations due to health and environmental concern. The end result is an increasingly challenging situation for farmers who are left with fewer efficient herbicides.

Weed control is one of the most important factors in all agricultural production. Weeds compete with crop plants for moisture, nutrients and sunlight and will have a significant negative impact on yield without sufficient weed control. Typical weed control methods for row crops include a combination of pre-emergence herbicide application, pre-emergence tillage, mechanical row harrowing and post-emergence herbicide application - if a selective herbicide or crop resistance is available (Slaughter et al., 2008; Fennimore et al., 2016).

In 2008, the European Commission withdrew the approval for several herbicides, among them herbicides with Propachlor as the active ingredient (European Commission, 2008). The herbicide was a health risk and had been documented contaminating ground water and harmful to aquatic life. The consequence to farmers of some cabbages and rutabaga was that they lost access to their most effective herbicide. In Norway this spurred a joint project with farmers and the Norwegian Extension Service in the search for alternative weed control methods, which one could say marked the start of the work presented here.

The weed that occur in between rows, inter-row weeds, can be controlled by row-harrowing, flaming or shielded spraying. Whereas the in-row weeds pose a greater challenge for the farmers. In lack of selective post-emergence herbicides they are left with few other options than manual in-row hoeing by hand, which is much more expensive than conventional spraying.

In the past 10–20 years we have seen a significant push to bring new

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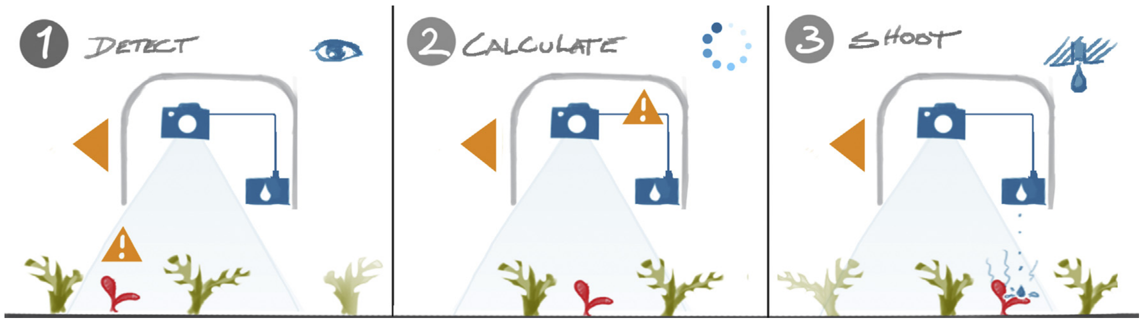

Fig. 1. Visualization on Drop-on-Demand herbicide application.

methods to the farmers to control in-row weeds. And for transplanted crops, there are methods available with vision-controlled in-row harrowing such as the *Garford Robocrop In-row weeder, Steketee IC Weeder* and *F. Poulsen Engineering Robovator*. The transplanted crops are relatively sparse and allow for these methods, as well as selective spraying where two notable examples are the companies *BlueRiver Technologies* and *Ecorobotix*.

Seeded crops present a greater challenge as there isn't enough room in between crop plants to allow for a mechanical hoe to pass in and out of the crop row. Herbicide application either requires a selective herbicide which does not harm the crop, or a better resolution application to not affect the crop. DoD herbicide application, Fig. 1, is one of the most promising technologies for controlling weeds in the plant row (Fennimore et al., 2016; Slaughter et al., 2008). The resolution in this paper is taken to the extreme by controlling individual droplets of herbicide, Fig. 1.

The essence of DoD spraying is to detect the weeds within the plant row, and selectively shoot droplets of herbicide on those weed leaves. By targeting only the weed leaves, the crop and soil are left unaffected, which allows for the use of broad spectre herbicides that would normally harm the crop.

We have focused much of our attention to carrots, as we consider it a good example of the more challenging crops. It is a seeded culture which account for 6.25% of Europe's harvested area for vegetables, with 2.6 million Ha. It is a high value crop with a gross production value for Europe above 3 billion USD in 2014 (FAO, 2014).

Carrot competes poorly with weeds especially in the early stages, as documented by Swanton et al. (2010) in a field trial in Ontario, Canada. The critical weed-free period for carrots was found to be 450 growing-degree-days (3–6 weeks at 10–20 °C), or until the carrot plants have reached the six-leaf stage.

While there are commercially available products for in-row mechanical hoeing, we are not aware of other commercially viable projects providing a DoD weed control system. This paper will present the newly developed autonomous robot platform shown in Fig. 2, and a novel system for drop-on-demand (DoD) application of herbicide. Finally, successful results from laboratory and field tests are reported.

We also present a system for flushing the valves, and handling excess spray liquid.

2. State of the art

The available products for guided hoeing and selective thinning are paving the way for further advances in automatic weed control in speciality crops. Our attention will be focused on precision-spray application targeting individual weeds - a domain which is yet to see its first commercially available solution.

One of the first demonstrations of a Precision-Spray robot was by Lee et al. (1999) as early as Lee et al. (1999). They developed a robot for controlling weeds in tomato crops. The robot was equipped with an Cohu RGB camera which information was digitized to 256 × 240 pixels at 8 bit per channel. The processing was done by a 200 MHz Pentium Pro CPU running MSDOS. The system recognized 73% of the tomato plants and 69% of the weeds, and was able to treat 48% of the weeds at a speed of 0.8 km/h.

Fig. 2. The 2017 Asterix robot prototype in field trials in Central Norway.

Nearly 20 years has passed since then, and while the robots has become incrementally better, we are yet to see weeding robots make an impact on the use of herbicides in agriculture. A thorough overview of this field can be found in Fennimore et al. (2016) or Slaughter et al. (2008), while we here will focus on a few relevant technical aspects.

2.1. Drop-On-Demand herbicide application

A challenge presented by Lee et al. (1999) is to increase the accuracy, precision and efficacy of the herbicide application. This effort involves everything from the design of the droplet forming mechanism, the fluid dynamics of the droplets, the droplets retention on the weed leaves, the choice of active ingredient, to the motion estimation and targeting algorithm.

Most of the previously presented systems for DoD herbicide application has either used adapted industrial print-heads (Lund and Mathiassen, 2010; Midtiby et al., 2011) or an array of solenoid valves and needles (Søgaard and Lund, 2005; Lee et al., 1999; Nieuwenhuizen, 2009) to form droplets. There is also a presented paper by Basi et al. (2012) where a pneumatic valve is presented for better dosing and formation of individual droplets. The fluid dynamics of the in-flight droplets has been investigated by Lund and Mathiassen (2010) and Lund and Olsen (2010). They describe the disintegration of droplets and the effects of altering the viscosity and surface tension of the fluid. We expanded on this and also explored the effect of the electrical control signal to the solenoid valve on the droplet formation in our experiments presented in Urdal et al. (2014).

Lund and Mathiassen (2010) and Lund et al. (2006) demonstrated that herbicide droplets formulated with glyphosate (27 μg per plant) can effectively control *Solanum nigrum* L., (Black Nightshade) a weed which is resistant to most selective herbicides. Midtiby et al. (2011) presented a simulated row crop trial where plants passed under the system on a conveyor belt at 0.5 m/s. The system was able to effectively control weeds larger than 11 × 11 mm, which gave good results on *Brassica napus* L. (oilseed rape) and to some extent *Tripleurospermum inodorum* (L.) Sch. Bip. (Scentless Mayweed). Koukiasas et al. (2016) demonstrated that *Galium aparine* L. (Cleavers) is effectively controlled with 19.3 µg of glyphosate per plant.

2.2. Leaf classification

Weed and crop classification has largely followed the classical approach of segmenting plant material from the background soil, for subsequent classification based on shape, color and texture features. Several systems have incorporated a Near-Infrared (NIR) channel to enhance the soil segmentation, e.g.: Nieuwenhuizen (2009). These classifiers has been demonstrated with high accuracy. They are however highly reliant on shape features and do not demonstrate satisfactory robustness when challenged by overlapping leaves and irregularities such as specular reflection from water droplets. There has been much effort invested in improving these algorithms (Fennimore et al., 2016). One example is Haug et al. (2014), who was able to circumvent the reliance on segmenting individual plants by implementing a form of sliding-window classifier. As a result, the classifier was robust to overlapping leaves.

In recent years there has been an important shift in Computer Vision towards deep learning. In nearly all domains we see classification tasks being taken over by deep convolutional neural networks (Deep CNN). These methods are also making their way into weed detection. One out of several examples is Milioto et al. (2018), who demonstrate pixel-wise semantic segmentation into weed and crop.

2.3. State-of-the art in Agricultural Robotic Platforms

There is a significant body of research and industrial push towards robotization in agriculture. There are philosophies towards automating tractors, building specialized robots for each task and towards making highly versatile and modular robots. A selection of comparable robots that have been presented for weed control is shown in Fig. 3.

Modularity has been uphold as an important design criteria for the Armadillo (Nielsen et al., 2012), Naïo Dino from *Naïo Technologies* and the Thorvald II platform (Grimstad and From, 2017) which can be customized to different configurations. Thorvald II, BoniRob, (Fig. 3a and c), and Naïo Dino have drive and steering on all four wheels. This enables holonomic control of the robot: The robot can navigate freely in all directions, handle tight environments such as greenhouses and the front and rear wheels can follow the same tracks through a turn. This comes at the cost of having 8 motors for steering and drive.

The AgBot II shown in Fig. 3d and presented by Bawden et al. (2017) is a robot platform for weed control, set up with differential drive front wheels and two rear castor wheels. The design emphasizes modularity and ease of on-site assembly of the system. A docking container covered with solar panels provide the power needs for charging, and the system has been tested with a range of chemical and mechanical weed control implements (McCool et al., 2018).

A more minimalistic approach has been taken by the Swiss company Ecorobotix who are working on a fully solar powered robot, Fig. 3b, which applies a micro-dose of herbicide by two robotic parallel arms.

The systems described above are intended to be a representative selection, and not an exhaustive review of the field, as there are several other systems that could have been mentioned.

3. System requirements and specification

In this section we will present the requirements for the robot. We have performed experiments and data collection in cooperation with vegetable producers for ten years. Through this work we have built up an understanding of the challenges at hand and how a robotic system for weed control can generate value for the farmer.

We have worked with producers of carrots, leeks, salad, cabbages, bush beans and spinach in Norway and Germany, while we have the most experience with carrots. The farmers we have cooperated with run a combination of conventional and organic production.

We envision the robot to be a tool for the farmer that integrate well with their existing growing practices, that does not require alteration on the cultivation practices. With regards to in-row weeding, the challenge and need is stronger with seeded cultures, than with transplanted cultures. A requirement for our system is to work with seeded row cultures. A set of design requirements are listed in Table 1, and detailed in the following paragraphs.

3.1. Cultivation methods

We are using carrots as a proxy for a larger group of row cultures with comparable cultivation methods. Carrots are seeded in three rows on a flat lifted bed, or on two ridges in between the wheel tracks, as illustrated in Fig. 4. Each row is typically double- or triple-seeded in carrot cultivation, a triple row has typically 5 cm spacing between the seed lines. The track width vary between producers, i.e. the width from center of the left wheel to the center of the right. One producer will typically run all their equipment at the same track width and it is usually in the range of 1.6–2.1 m. Some larger productions use wider machinery for bed forming and seeding. Distance between tracks are then triple or wider, apart with continuous beds or ridges between. This is more common in transplanted crops such as salads and cabbages, while it is also used by some producers of carrots, turnips, spinach, etc.

The system must have one DoD unit for each crop row, and be height adjustable to adapt for the different cultivation methods. The width of the crop rows and seed-lines define the operational area for the DoD array. We need to control weeds in the crop row with a sufficient margin to overlap with the conventional tools for inter row weed control, such as guided harrows and weed brushes.

3.2. Robot and operational requirements

Setting requirements for the robotic platform is more about interpreting the producers needs, than it is an exact science. Together with producers we have envisioned several use cases and scenarios for the robot. The robot is designed to be a highly specialized tool for in-row weed control, focused on that task alone. The focus allows for a tailored and lightweight robotic platform.

The design requirement for the robot is a gross weight under 300 kg, both with regards to minimizing soil compaction and to limit the risk in human robot interaction. A target nominal operation speed of 0.8 m/s was selected on the basis of safety, area coverage and timing requirements imposed on the DoD system.

The fields and operation area is normally relatively flat, and we have set a nominal 5 deg incline specification. This will allow sufficient headroom for the variety of fields, and to some extent account for wet or high friction soil conditions. The extreme climbing requirement at 40 deg has been chosen to allow loading on and off trailers, and climbing over thresholds to access the field.

The system should come at a low cost of adaptation. The system does not require significant new infrastructure, and the robot is able to operate continuously throughout a working day. The robot is able to transport itself between fields, and for longer distances it can easily be loaded on a trailer with ramps.

3.3. Operator health and environment

The handling, loading and mixing of herbicides integrate with

(a) DeepField Robotics BoniRob, photo courtesy of Bosch AG

(b) Ecorobotix, photo courtesy of Ecorobotix Ltd

(c) Thorvald II platform, photo courtesy of Saga Robotics AS.

(d) AgBot II, photo courtesy of Queensland University of Technology

Fig. 3. A selection of other robot platforms presented in literature.

Table 1
Main technical specifications of the robot in-row weeding system.

Description	Value	Unit
Vehicle mass	300	kg
Nominal speed	0.8	m/s
Transport speed	1.4	m/s
Nominal incline	5	deg
Max incline[a]	40	deg
Track width	1.6–2.1	m
DoD operation width	168	mm
DoD resolution	6	mm

[a] Max incline for short time loads, e.g. trailer ramps, thresholds, etc.

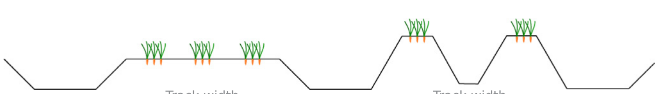

Fig. 4. Carrots are typically triple-seeded in three rows on a lifted bed (left), or on two ridges between the tracks in the field (right). The track width is the distance across the row, measured from the center of the wheels of the machinery.

existing work flows, and does not present additional exposure of herbicides to the operator or environment. Variable rate application presents a challenge to predicting the amount of herbicide required for a field. Excess herbicide is to be diluted and dispensed according to label, or transferred to a process for hazardous waste.

4. Robot design

The overall design goal is to make a specialized robot, best adapted to the task at hand: Efficient weed control in row crops. This implies that we have not attempted to design a modular and versatile robot - rather a simple, robust, maintainable and cost efficient system for DoD weed control in row crops.

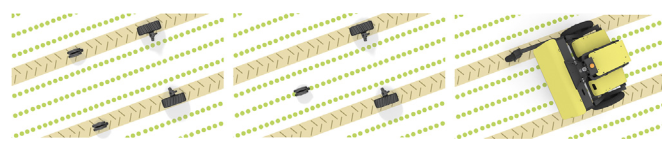

Fig. 5. The off center 3-wheel configuration of the robot, allows for a lighter design with fixed wheel suspension, and only two motorized axes.

4.1. Three wheeled design

A common cost-effective robot design is using differential drive front wheels and rear castor wheels as the robot presented by Bawden et al. (2017). If you were to reduce to one castor wheel, Fig. 5, the conventional design is to center the rear wheel. This is obviously not a good design for row crops, as the wheel would damage the crop - one could say it would *trample the salad*. Therefore we propose to use one off-center rear castor wheel. This necessitates a design with special care to weight distribution and stability.

A four-wheel design would require wheel suspension for the wheels to maintain ground contact when moving over uneven ground. The operational speed of the vehicle is sufficiently low such that we do not require a wheel suspension system from a vibration perspective. Three wheel design are not common, and we believe they have been disregarded in design of agricultural robot, as a symmetric design would not be suitable for operations in row crops.

By designing the system with a asymmetrical three-wheel configuration, we obtain a minimal wheel configuration while maintaining the systems suitability for operations in row crops. By designing the robot ground up, we obtain a highly cost-effective robot with a minimum of movable parts and good handling capabilities and stability.

4.2. Hybrid drive

The robot should be able to operate nearly continuously. The power requirements are outside of what can be delivered by solar panels on the available surface area, and the robot should require a minimum of additional infrastructure for its operation. Therefore the Asterix robot has been designed as a hybrid vehicle with a 48 V DC backbone and a four-stroke generator. The generator satisfies the average energy demands, while a battery bank ensures sufficient power during peak demand.

4.3. Concept for herbicide application

The resolution of the DoD array is determined by the crop culture and types of weeds we seek to control. The system is required to operate in the dense seed line of carrots, and effectively control weeds at early stages, including grass weeds with thin leaves. We have balanced these requirements, the technical feasibility and cost of a nozzle array, and arrived at a 6 mm lateral spacing of the DoD nozzles.

The longitudinal resolution is governed by the velocity of the robot and the DoDs maximum dispensing frequency. We have designed the system to maintain a 6 mm resolution at 0.8 m/s. The DoD modules are setup with 28 nozzles, giving an operational width of 168 mm, which leaves a margin for the row harrows towards the seed lines.

The spray controller and nozzle array is described further in Urdal et al. (2014).

4.4. Camera system and vision processing

The vision unit employs an Nvidia Jetson TK1, with an embedded camera unit using the Omnivision 4682 4MP sensor. The computer, camera and LED flash is embedded in the DoD unit, making the unit fully modular and compact design, Fig. 6. The DoD modules are mounted on a height adjustable beam, to account for variations in height between the wheel tracks and crop rows.

The vision pipeline is illustrated in Fig. 7. The raw images are debayered to the RGB and HSV color space. The Hue and Saturation channels are used for segmentation of plant material from soil, which forms the mask. The mask is processed to separate individual leaves, and reduce noise. For each connected component in the resulting image, we compute a feature vector based on shape, texture and color. A support vector machine classifies each feature vector as either weed or crop which is used to generate a spray map. The corresponding crop map is used to mask out a safety margin in the spray map.

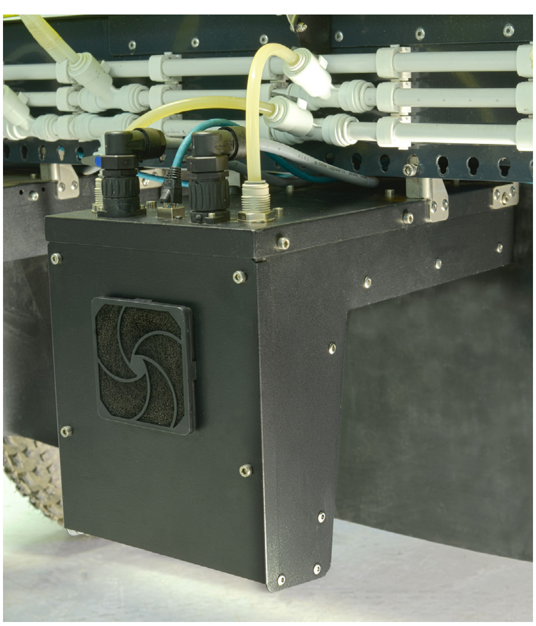

Fig. 6. The Blythii module is a self-contained module for the machine vision and droplet application. The interface to the robot is the supply and return line for spray liquid, 48 VDC, CAN-bus and ethernet.

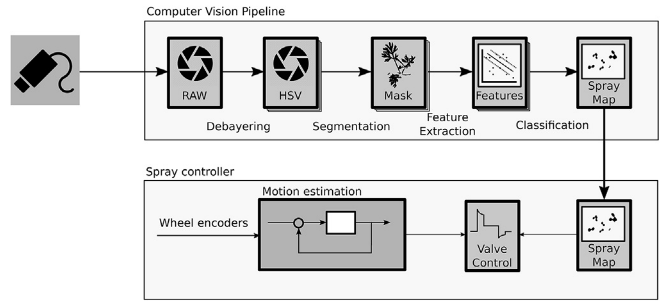

Fig. 7. Every 200 ms the Blythii module captures an image, segments and classifies the image to generate a spray map. This is transferred to the Spray Controller which estimates its motion and excites the solenoid valves according to the spray map.

The spray map is transferred to the spray controller, which continuously estimates the relative motion by integrating the wheel encoder signals received over CAN-bus. The time-stamp of the spray-map, and the motion estimation is used to localize the current position of the valve array relative to the spray map. When a valve enters an active cell of the spray map, the valve is triggered and a droplet is dispensed on the weed, accounting for the droplet flight path and vehicle velocity.

4.5. Navigation unit

The navigation unit is based on the same computer hardware as the DoD modules, with the addition of peripherals for connectivity through mobile LTE/3G, WiFi when available, a GPS module and a forward facing camera for row detection. It also has an embedded CAN-bus module to connect to the backbone and command the Brushless DC (BLDC) motor controller.

The computer runs the open source Robotic Operating System (ROS), and for localization we utilize the Extended Kalman filter in the ROS package robot_pose_ekf. We use the forward facing camera to detect the seed lines: We assume a flat surface in front of the robot, and perform a homography transform of the image to obtain an orthonormal perspective. The image is segmented using a threshold on Green over Red*Blue channels, which become the input for a Hough Transform detecting straight lines in the image. We group the resulting line candidates to left, center and right, filter away outliers. The remaining line candidates are forwarded as measurements to a dedicated extended Kalman Filter estimating the current crop row location and heading in the global reference frame. The process is illustrated in the screenshot from the ROS/ Gazeebo simulator in Fig. 8. In our experience the flat surface assumption holds well in most field conditions, for

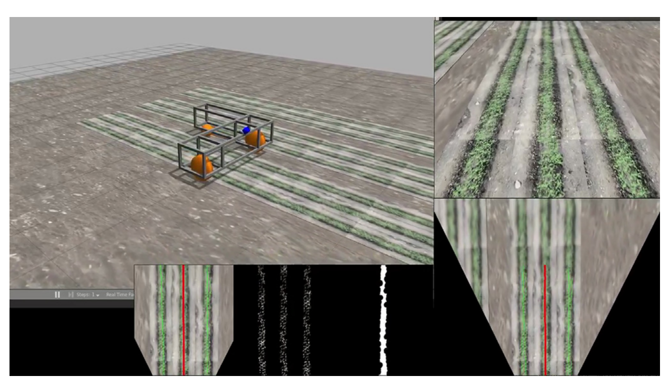

Fig. 8. The simulator of the system is used to develop the row following algorithms, and headland turning. The upper right shows the view of the forward facing camera. Using a homography transform with the assumption of a flat surface in front of the robot, we convert the image to an orthonormal view as shown in the lower images.

the limited field of view that we operate with.

We have previously presented a non-linear model predictive control algorithm for row following Utstumo et al. (2015). The purpose of the controller is to prevent the rear castor wheel from damaging the crop, by limiting the steering control input. The complex implementation and our experience with path following controllers presented in Dørum et al. (2015), has led us to utilizing a simple line following algorithm, which better handle the context switching between row following and navigation in the headlands to enter the next row.

4.6. Valve flushing and management of excess spray liquid

While we have performed experiments to test and improve our precision and accuracy, we have experienced issues with clogged nozzles and residues of the spray liquid inside the valves. In the development, we have emphasized robustness and repeatability of our valve system, while this has not been given much attention in the literature.

The herbicides are to a varying degree corrosive liquids, and will leave residues if they are left in the valve system. The residue may prevent the valves from sealing properly, and we are left with a leaking valve, potentially damaging crop plants. To obtain a robust and reliable DoD system we have implemented measures to counter these effects. Our most important tool in this context is to regularly flush the valves, and ensure that the valves are clean when left unused for an extended period of time.

In Fig. 9, the system and its functionality is illustrated. The spray liquid in the main tank is continuously circulated by the pump. The liquid goes through a filter to remove any particles that could clog the valves and nozzles. The liquid circulates out using the supply line to all the DoD units, where some of the liquid end up as droplets deposited on weed leaves. The bulk of the liquid circulate back through the return valve, which regulates the pressure in the system.

To flush and clean the valves and supply lines, we have fitted the robot with two extra tanks. Tank A holds the spray liquid, while Tank C holds clean water for flushing the system. The return liquid from a flushing operation goes to tank B.

With a variable rate application of herbicide, it is required to do an estimate of the herbicide use through a field, and minimize the number of refills and the remaining amount left at the end of treating a field. Any remains in the herbicide tank will either need to enter a waste management system, or for some herbicides they may be properly deposited on organically active soil, as specified by their label.

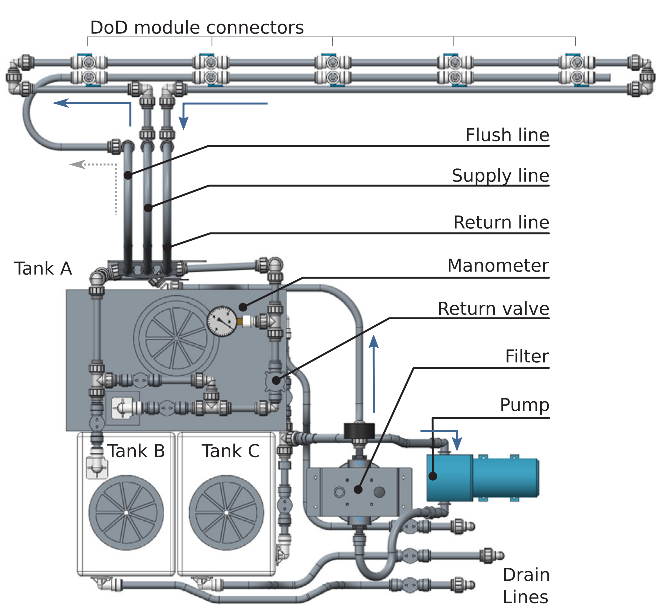

Fig. 9. The spray liquid system supplies pressurized spray liquid to the DoD modules. The liquid continuously circulates through the DoD modules to ensure that the liquid is properly mixed.

5. Efficacy of single herbicide droplets

The objective of these pot trials was to find a liquid suitable for DoD application and with good weed control properties at the relevant growth stages, i.e. two - five true leaves.

5.1. Materials and methods

In these trials, we have focused on finding an appropriate application and dose for four common weeds in carrot crops. *Tripleurospermum inodorum* (L.) Sch. Bip, (Scentless Mayweed), is a challenging weed as it carries visual similarities to the carrot leaves in early stages. In addition it is resistant towards aclonifen, which is the most commonly used herbicide in carrots, so it requires an additional herbicide, like metribuzin, to be controlled by conventional spraying. The first leaves of *Chenopodium album* L., (Fat-hen), have a hairy and waxy-coated surface. Water droplets typically bounce off its leaves, and it presents an important adhesion test for our DoD system. *Poa annua* L., (Annual meadowgrass), is an annual grass weed and *Stellaria media* (L.) Vill., (Common Chickweed), is an annual broadleaf weed.

The technical setup is analogous to what was presented by Urdal et al. (2014). We are using the same control circuit and the same solenoid valve and nozzle (INKX0514300A and INZA4710975H) from *The Lee Company*.

This experiment was performed as two separate pot trials, which were sprayed on February 4 (Trial 1) and February 12 (Trial 2) in 2016. As an extension to previous studies on DoD herbicide application, which use glyphosate as the active ingredient, we have included iodosulfuron in our experiments. The herbicide solutions are described in Table 2. In each of the pot trials, there was a control which received three droplets of our base solution containing only the blue dye and additives for liquid properties. Each herbicide was first diluted with water, and then diluted with the base solution, as described in Table 2. In total there was 200 pots with one weed plant per pot. There was 5 pots for each combination of species and liquid formulation, (4 × 10). There was one weed plant per pot, and there were 5 replicate pots for each combination of weed species and liquid formulation. In total 200 pots (5 replicates × 4 weed species × 5 liquid formulations × 2 trials) were included.

The droplet volume was measured to 1.16 μL by dispensing 1000 droplets into a container on a digital scale. This measure was verified by dispensing 1000 droplets into a 1.5 ml graduated test-tube.

The above ground biomass for each pot was cut and weighed on March 1. The fresh-weight datasets of the aboveground biomass per species and trial were analyzed separately using ANOVA GLM considering replicate pots and liquid formulations as random and fixed factors, respectively. The resulting means were compared using Tukey test at significance level = 0.05. Model assumptions like normal distribution of residuals and equal variances were tested by Anderson-Darling test and visual inspection of residual plots.

5.2. Results and observations

Treatments A2 and A3 with glyphosate in the first trial had poor droplet quality. We observed satellite droplets being formed mid-air and poor leaf retention. Nearly no herbicide was retained on the leaves as can be seen in the example in Fig. 11. The A4 and A5 solutions with iodosulfuron produced well formed droplets and had high leaf retention, as shown in Fig. 12. The liquid viscosity and surface tension was adjusted by using high speed photography and experience from earlier experiments (Urdal et al., 2014) for the following pot trials. Four liquids with glyphosate was tested in Trial 2, where the leaf retention and droplet performance was good.

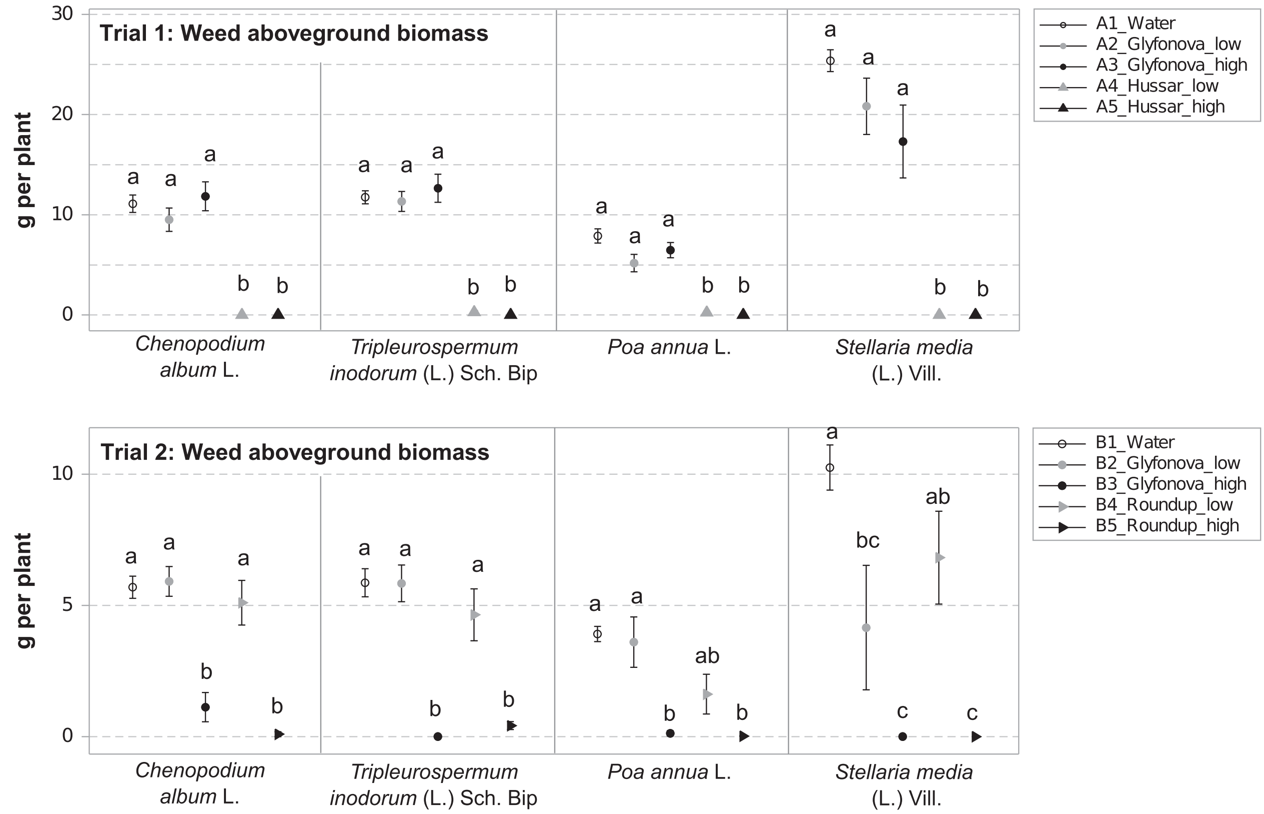

Fig. 10. The fresh weight of the four weed species in the two pot trials, 25 (trial 1) and 17 (trial 2) days after herbicide treatment (cf. Table 2). A1 and B1 serve as controls, represented by the leftmost bar in each plot. The error bars are one standard deviation from the mean, and the letters above indicate the grouping by the Tukey test. In trial 1 only the two treatments with iodosulfuron, A4 and A5, gave significant reduction in weed biomass compared to the control, A1 (water only). In trial 2, the two treatments with high dose of glyphosate, B3 and B5, gave significant reduction in weed biomass.

Table 2
In each of the two pot trials performed on February 4 (A) and 12 (B) 2016, there was one control (water) and four different herbicide treatments. The Active Ingredient (A.I.) of both Roundup Flex Plus and Glyfonova Plus is glyphosate, while Hussar OD is based on iodosulfuron. Each liquid was diluted in two steps, and the plants were treated with 3 droplets of 1.1 µg volume each.

	Trade name	A.I. conc g/L	1. dil. %	2. dil. %	A.I. conc g/L	Dose plant µg
A1[a]	–					
A2	Glyfonova plus	360	2.8	2.0	0.20	0.61
A3	Glyfonova plus	360	2.8	25.0	2.52	7.56
A4	Hussar OD	100	10.0	0.5	0.05	0.15
A5	Hussar OD	100	10.0	10.0	1.00	3.00
B1[a]	–					
B2	Glyfonova plus	360	2.8	2.0	0.20	0.61
B3	Glyfonova plus	360	2.8	25.0	2.52	7.56
B4	Roundup Flex Plus	480	2.1	2.0	0.20	0.61
B5	Roundup Flex Plus	480	2.1	25.0	2.52	7.56

[a] Same base solution as A- and B-, no A.I.

In trial 1, the glyphosate treatments, i.e. A2 and A3, gave no weed control effect, whereas the iodosulfuron treatments, i.e. A4 and A5, gave very good control Fig. 10. The lack of effect of the glyphosate droplets was unexpected.

The groups A2, B2, B4 and A3, B3, B5 have the same active ingredient and dose, but different liquid properties. The liquid formulation in A2 and A3 treatments had poor leaf retention properties. After having revisited the liquid viscosity and surface tension, the high doses of glyphosate formulations in trial 2, i.e. B3 and B5, demonstrated a good ability to control weeds. With 7.56 µg glyphosate per plant we could effectively control the four weed species.

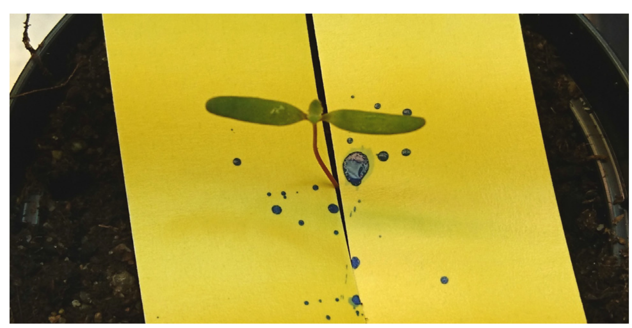

Fig. 11. *Chenopodium album* L. after DoD application of liquid A3 with glyphosate. The liquid had very poor leaf retention properties, and satellite droplets were formed mid-air. No liquid is visible on the leaves, while the yellow liquid sensitive test strips highlight the droplets by turning blue. The droplets have either disintegrated in-air or bounced off the leaves. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

6. Field trial on efficacy of Drop-on-Demand

Throughout the past years the Asterix robots has been in the field with a team of vegetable farmers in Norway. To perform an end-to-end test with a new build of the robot and to document the efficacy of the system, we set up a trial in 2017.

6.1. Materials and methods

A part of the field was seeded with carrot in late August after the regular harvest specifically for this trial. The trial had two different treatments, herbicide (glyphosate) and unsprayed control, and each

Fig. 12. *Stellaria media* (L.) Vill. after DoD application of liquid A5 with iodosulfuron. The three applied droplets have spread and achieved good contact with the leaf.

Fig. 13. The robot at the start of the field trial. Only the center of the three carrot rows was used in the experiment.

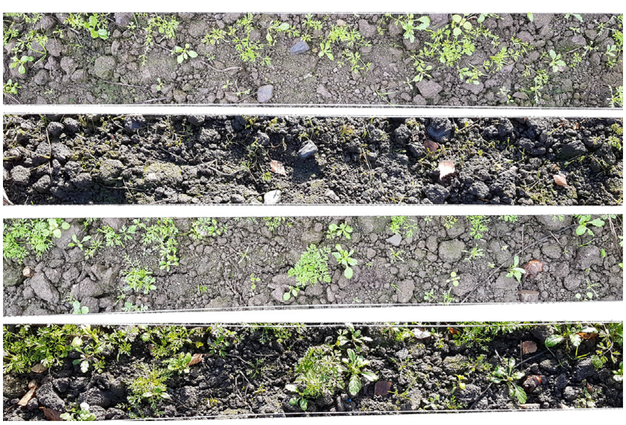

Fig. 14. Two uppermost images: same plot (plot No. 1001) before and 17 days after glyphosate application with the robot. Two bottom images: untreated plot (plot No. 1002) October 2 and 19.

treatment was replicated ten times in a randomized block design. The plots treated were 2 m long, and were laid out along the crop rows. The areas assessed were 12 cm wide and 1 m long. The field is shown in Fig. 13 and two plots before and after treatment are shown in Fig. 14.

The trial was designed to evaluate the effect of the DoD system in the field. To eliminate errors from misclassification, all weed and carrot plants were treated. The trial represents an end-to-end test of the camera system, plant detection, generation of the spray-map, motion estimation, droplet target and shooting and the overall robot system.

The robot treatment was done September 28, and the plots were surveyed for number of carrot and weed plants (by species), by a skilled and experienced person in weed assessment October 2, and October 19. The observed weeds and their average occurrence in the plots on October 2 is presented in Table 3, on average there was 548 carrot plants per m^2. Images were recorded of all plots with a hand-held

Table 3
The weeds observed in the field trial October 2 with their occurence per m^2 as an average over the 10 plots surveyed.

English name	Latin name	$\frac{\text{plants}}{\text{m}^2}$
Scentless Mayweed	*Tripleurospermum inodorum* (L.) Sch. Bip.	186.4
Annual meadowgrass	*Poa annua* L.	126.5
Fanweed	*Thlaspi arvense* L.	73.5
Field pansy	*Viola arvensis* Mur.	9.8
Prickly sowthistle	*Sonchus asper* (L.) Hill	4.5
Purple Deadnettle	*Lamium purpureum* L.	1.5
Fumitory	*Fumaria officinalis* L.	1.5
Storksbill	*Erodium cicutarium* (L.) L'Hér.	0.8

camera the two latter days (Fig. 14). Since the air temperature was relatively low, the four days between robot treatment and first weed assessment was considered unproblematic.

We have utilized the images to estimate the relative green index (RGI) of each plot, to evaluate the efficacy of the treatment, in conjunction with the field observations. The RGI is computed by first computing the Triangular Greenness Index (TGI) (Raymond Hunt et al., 2011) of each pixel: $TGI = 1.0Green - 0.39Red - 0.61Blue$. We then segment the images using the average Otsu threshold value for all the images (Otsu, 1979). The RGI is the number of pixels above threshold divided by total pixels.

6.2. Droplet volume and herbicide liquid

The spray mixture was the same as in treatment B3 of the pot trial described in Table 2. The active ingredient was glyphosate in a concentration of 2.52 g/L. The droplet sizes was estimated by shooting 1000 droplets through 7 individual nozzles into an empty container on a digital scale. The scale has a precision of 0.1 g, and the resulting volume per droplet is estimated to 2.1 µL per droplet.

6.3. Experimental results

On Oct 19, the control plots were considered to have a substantial weed infestation, and the surveyor opted to document the plots by images, rather than counting individual weeds. The treated plots were surveyed and the only observed weeds were 12 seedlings of *Poa annua* L., (Annual meadowgrass), an average 10 plants per m^2. It is possible that the *P. annua* seedlings were too small to have been detected by the vision system, or accurately targeted by the DoD system at the time of treatment. Their size however indicate that they have emerged after treatment.

We have analyzed the difference in RGI between the two treatments (glyphosate and unsprayed control) by a pairwise Tukey method and 95% confidence interval. Model assumptions like normal distribution of residuals and equal variances were tested by Anderson-Darling test and visual inspection of residual plots. The two groups were significantly different, and on average the treated plots had a reduction in RGI by 6.3% and the untreated an increase by 5.6% of the image area, as shown in Fig. 15.

The RGI measure will include leaves that have died, but still green enough to pass the threshold. To evaluate the systems ability to control weeds in the field, we rely on both the RGI assessment and the field observations by the surveyor. All the treated plots were surveyed after treatment, and *P. annua* (Annual meadowgrass) was the only weed present. The *P. annua* seedlings had likely emerged after treatment. The RGI measures show an increase in green index for all untreated plots, thus we consider the trial a demonstration of successful weed control.

7. Discussion

The lab trials demonstrate that the four selected weeds can be

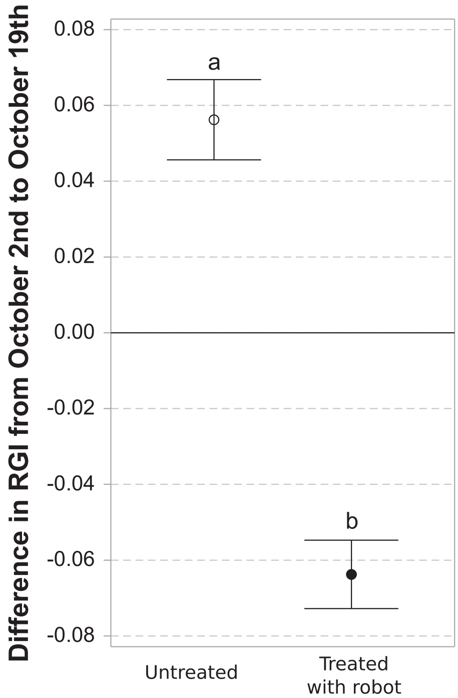

Fig. 15. The change in relative green index in the treated and untreated plots, with error bars of one standard error. The letter indicate the grouping by Tukey HSD test. There was growth in the untreated plots, and a reduction in green index in the treated plots.

effectively controlled by DoD application of herbicide with doses as low as 7.56 µg glyphosate or 0.15 µg iodosulfuron, per plant. In field conditions we have demonstrated total weed control with the system using droplets with 5.3 µg glyphosate content.

7.1. Reduced herbicide application

We sprayed approximately 10% of the area with our droplet spacing of 6 mm in the field trial, which is analogue to an application of 191 g glyphosate per hectare. The label application for Glyfonova Plus ranges from 540 g/ha to 2880 g/ha depending on the types of weeds and weed pressure (Cheminova AS, 2015). This yields a herbicide saving in the range of 73–95% comparing with label glyphosate application. Based on our findings from the lab trials, we expect to reduce the droplet size to 1 µL and that the weeds will cover less than 5% of the area we treat, reducing our glyphosate application rate to below 50 g/ha.

A more relevant comparison is towards the commonly used selective herbicides in carrots today. The combination of aclonifen and metribuzin is the most common application in conventional production of carrots, with a maximum of 3 treatments with a total application of 1050 g/ha aclonifen and 106 g/ha metribuzin.

A treatment scheme with the robot and the DoD system, would consist of 2–3 treatments in combination with mechanical weed control in between the rows. Building on the experience from the lab and field trials, we would estimate a total application of 50–150 g/ha glyphosate. This represent a ten-fold reduction in applied herbicide.

7.2. Reducing environmental and health risks

The amount of herbicide used is the main factor regarding the benefits towards health and environmental impact. All the herbicides we are dealing with are toxic to aquatic organisms, and to a varying extent they pose a health risk. Metribuzin is toxic if swallowed, and aclonifen is known to cause allergic skin reactions and is suspected of causing cancer.

The herbicides we replace them with have less severe health risks associated with them, even with the health impact of glyphosate being under heavy debate it is clear that the selective herbicides such as aclonifen and metribuzin pose a greater health risk. Iodosulfuron and glyphosate does not have health risk classifications beyond its potential to causing eye damage.

A DoD system produces larger droplets than a regular sprayer, and most importantly it does not produce aerosols. This reduces the exposure to operators and people near the field. The design of the robot and its implementation in the producers workflow will have to minimize the operators exposure to the herbicides, and enable a safe waste management system for excess herbicide and empty containers.

7.3. Impact on need for manual weeding in vegetable crops

While the environmental and health benefits of the system are significant, the DoD method will not see adaptation with vegetable producers unless it provides value to the producer. From experience we know that producers are frequently having to resort to manual weeding. They may be dealing with herbicide tolerant weeds or the weather conditions have not allowed for efficient herbicide application. Manual weeding is very much a candidate for automation, it strikes two out of three on the phrase “Dull, Dirty and Dangerous”. The labour is inherently seasonal, and finding skilled labour willing and able to take on the work is challenging - and vulnerable to changes in immigration legislation as many are migrant workers.

A DoD robot can increase the quality of weeding, reduce the reliance on seasonal workers and improve food quality as the product is not affected by the herbicides.

8. Conclusion

The robot presented here has been designed with the specific task of Drop on Demand herbicide application in mind. The robot is tailored to this purpose with cost, maintainability, efficient operation and robustness in mind. The three-wheeled design is unconventional, and the design maintains maneuverability and stability with the benefit of reduced weight, complexity and cost. The robot and DoD-system is adjustable to account for differences in cultivation methods, number of crop rows, track width and height of the crop row. The forward facing camera, and navigation unit enables row following through the field. A combination of vision and GPS localization detects the end of a row, and aids the navigation in the headlands.

The current DoD modules treat a width of 168 mm with individual droplets of herbicide, spaced 6 mm apart. The efficacy of the DoD method is investigated in lab trials with four weed species, including one grass species and three dicot species. The weeds are effectively controlled by 7.6 µg glyphosate, and 0.15 µg iodosulfuron per plant.

The robot effectively control all weeds in the field trial with a ten-fold reduction of herbicide use. The field trial serves to demonstrate that our DoD system is a capable alternative to conventional spraying. The DoD system can reduce the amount of herbicides used by more than 90%, utilize herbicides with lower environmental and health risks, reduce or even eliminate the need of manual in-row weeding.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.compag.2018.08.043.

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