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An Autonomous Field Robot to do Site-Specific Weed Detection and Targeted Herbicide Application in Row Crops

Dr. Hans Meijer[1], Dr. Sofia Dimitriou[2]
[1] Department of Field Robotics, Wageningen University & Research, Wageningen, Netherlands
[2] Department of Agricultural Engineering and Automation, University of Thessaly, Volos, Greece
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Abstract:
The trend in reducing the application of herbicides in farming has put much attention to precision weed control. The paper is the result of the development and the field testing of an autonomous robot to detect weeds on the site and locally apply a herbicide in row crops. The robot employs convolutional neural networks (CNNs) technology in real-time detection of weeds and variable-rate actuator in accurate herbicide treatment. Areas covered in the field tests in the Netherlands in the maize and sugar beet fields indicated that herbicide use was reduced by 71.5 per cent with an efficacy of 94.2 per cent of weed control. The robot reached an operating coverage of 1.6 hectares per hour, and very little disruption to crops. The findings indicate that AI-enabled robotics has great promise in sustainable crop protection and it can provide a solution to overcome herbicide reliance and efficiency improvement in precision farming.
Keywords: ***autonomous robot precision agriculture weed detection convolutional neural networks targeted herbicide application site-specific spraying agricultural robotics.***

1. Introduction

1.1 History of Herbicide Excess and Environment Disaster History

The advent of a lot of herbicides in agricultural activities has generated a lot of worry about their actual effects on the environment. The overuse of herbicide, in addition to causing soil degradation, water pollution, biodiversity loss, predisposes herbicides to resistance in plants. These environmental concerns have been of essence as farmers remain committed in the extensive use of chemical herbicides to control weeds. A surplus of the use of chemicals can be washed to the adjacent water bodies where it contaminates ecosystems and impacts aquatic organisms. Moreover, reoccurring application of herbicides results in the development of resistant strains of weeds, causing the traditional treatment of herbicides to lose its effectiveness creating a cycle that feeds into the more use of chemicals.

Besides, economic costs of using herbicides are very heavy since farmers continue to consume a huge share of their working expenses on the same. This has also contrived the need to have sustainable farming techniques that can be able to sustain high productivity and at the same time limit the adverse effects to the environment. There ensues the growing challenge to the agricultural industry to transform into more ecologically sound and responsible practices particularly in the problem area of weed control that is one of the most troublesome areas of crop cultivation production.(1)

1.2 New leadership of Precision Weed Management

To address these concerns, precision weed management (PWM) has been proposed since it offers a new solution to the problem. There we have precision agriculture, with all the current technologies of remote sensing, data analyzing, and machine learning, which may provide a more specific and effective control of weeds. Precision weed management through the application of higher level sensors and weed-detecting technologies and the ability to spray site-specifically, means farmers can apply chemical herbicides where they have to, minimizing the tools used, and minimize the environmental impact of such herbicides, and preserve biodiversity.

Under precision weed management, emphasis is made on site targeting where the herbicides are only sprayed in the sites where the weeds exist and the blanket application of a field is eliminated. It helps to use less herbicide overall, exposes fewer species to pressure and enables slower development of herbicide-resistant weeds. The usage of row crops such as maize, wheat and sugar beet create a serious problem in scalable precision weed control because crops and weeds are distinguished by a human operator. Nevertheless, soon with the development of autonomous robots and the ability to genuinely detect weeds using AI, precision weed management systems are on the rise.(2)

1.3 Goals of Making an AI-Based Autonomous Weed Control Farming Robot

This paper will introduce the process of creating an autonomous field robot that will identify the specific site of weeds and apply herbicide selectively in row crops. Its ultimate goal is to minimize the application of herbicides and sustain low levels of application with an effective control of weeds and also to enhance sustainable agriculture. The concept of convolutional neural networks (CNNs) is applied in the real-time detection of weeds by the robot which makes the robot to be able to distinguish between weeds and crops despite being made in the complex situations of the field. These CNNs are trained with huge datasets of crop and weed data, so that the robot can make an aerial decision of applying the herbicide.

Also the robot has variable rate actuators allowing optimal advantage and adjustment of herbicide application to apply enough depending on requirement of each area of field. The thesis behind this system is operational efficiency, which is maximized by reducing herbicide wasted amounts and crop disturbance, which is a major concern in automated field operations. The autonomous nature of the robot enables it to move around the fields on its own and offer live control of weeds over extended fields. With the combination of those technologies, the robot can be discussed as a major step in AI-based agricultural robotics and is likely to change the approach to the way weeds are controlled in new farming systems.(3)

2. System architecture and Prototype development

2.1 Hardware Summary, Mobility Platform, Sensors and Sprayers

The site specific autonomous field robot proposed to detect weed locations and target plants with herbicide is on top of modular and resilient base hardware platform which would perform efficiently in a row crop system. The robot has major parts that have synergy to perform their functions well, and this is achieved through the mobility platform, the sensors and the sprayers.

Mobility Platform:The robot is equipped on a wheeled platform whereby each wheel is driven independently, this implies that the robot can navigate the narrow crop field lanes, like that of maize and sugar beets with minimal disturbance on crops. The cross country type of wheels can be used on rough surfaces, on wet grounds, and different field conditions allowing the robot to move on flat and hilly grounds. The moving platform also has motorized steering and differential drive system, so it is easy to control the movements and the system would be stable enough to work with a high speed (up to 1.6 hectares per hour).

2.2 Sensors:The robot will be fitted with a range of sensors both with regards to detection of weed and navigation in the field:

Camera and vision systems: He/she robot has high-resolution cameras fitted to spot the weeds in real time, which is done courtesy of the convolutional neural networks (CNNs). The cameras used in them take the pictures of the field, which the on-board AI processes to identify crops and weeds. The CNNs are trained on huge databases to make sure that the robot is clear about the different kinds of weeds and how to distinguish them with the crops surrounding them.

LiDAR and Ultrasonic sensors: To navigate in the field and detect the obstacles, the robot has been installed with LiDAR (Light Detection and Ranging) and ultrasonic sensors used to come up with the terrain map and to detect any obstacle, like rocks or some rough or bumpy parts of the field.

GPS and RTK (Real-Time Kinematic) Systems: A-, B-connected: Then there is the use of a GPS system with RTK correction, which allows high precision of navigation and therefore accurate positioning of the robot in the row crops then it will have a series of defined paths to follow and will therefore be in a position to apply herbicides on a site-specific basis(4)

Sprayers: The robot system also includes the incorporation of variable-rate sprayers that have the capability of varying the amount of herbicide sprayed depending on the real-time process of detecting weeds. The sprayers have several nozzles each of which can be operated under control thus hitting the exact spot on the weeds with herbicide and sparing other crops. Delivery of the herbicide is also limited to the area only where the weed is concentrated and hence there is less wastage or less effect on the environment. The sprayers will also be made to match throughout the changing field conditions being responsive to the robot speed and terrain.

2.3 The Navigation Technology and the Use of Control Systems

The robot uses a centralized on board computer on which operations of mobility platform, sensors as well as the sprayers are synchronized. An inbuilt real-time control performs all the activities of the robot that takes the information captured by the sensors, and executes the data processes based on machine learning algorithms. An

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advanced autonomous control unit drives the navigation and decision of the robot, and this unit contains the following:

Path Planning Algorithms: Robot uses SLAM (Simultaneous Localization and Mapping) to plot the field and calculate the possible optimum path that will serve to navigate the field between crop aisles. This enables the robot to operate accurately and evades obstacles and transfer the herbicide most effectively

Real-time Communication System: The robot also has wireless communication systems so as to monitor and control it easily. The robot can be communicated with via an interface by the operators, who get real-time feedback to its activities and progress.(5)

2.4 Row Crop environment Mechanical Design Considerations

When designing the robot to work within row crop settings, a number of mechanical factors were given priority whereby the robot had the capability to maneuver within the narrow crop row (they are usually spaced 50-75 cm apart) without having to hit the plants:

Compact and Low Profile Design: This design served to make the robot smaller in extent and height, enabling it to readily fit in the crop rows and perform without causing any harm on crops. The robot is quite gentle on the crops so that there is little soil compaction and damage of roots.

Adjustable Suspension: The robot has a set of adjustable suspension so that it adapts to crops height and field state. This will enable the sprayers to be able to work the smoke by having an optimum distance between itself and the crop canopy as well as the weeds without regard to the size of the crop or landscape.

Lifespan and Availability to field: The material that is constructed out of the robot should be selective and provide durability and resistance to the elements so that the latter can work in different weather conditions and in the field such as wet ground or dry, or with dust and soil particles.

3. Weed Detection and Classification algorithm

3.1 CNN Training and Training Dataset

A Convolutional Neural Network (CNN) is the most important part of the weed detection system of the robot which has been trained to distinguish crop plants and weed species. The working of the CNN model will be based on real-time images coming in of the high-resolution cameras connected to the robot. Such pictures will then be used to train the CNN as the network extracts the most relevant features and other visual traits peculiar to weeds and crops.(6)

In order to train the CNN model, a broad series of pictures was prepared, which included the different representations of the crops and the weeds. The data involved maize and sugar beet experimental crops and the common weeds in those fields edged out commonly, including common lambsquarters, pigweed, and cocklebur. The dataset image was taken in the changing environmental conditions like the varying lighting conditions, the development stages of the weeds, and the different densities of the crop so that the model appears to be generalized and well transferable to the real-world conditions. The data were divided into train, validation and test sets, with the training set as the one to train the model to identify the characteristic properties of crops and weeds.

Also, in training, the CNN employed supervised learning and it was based on the labels that each image had with the help of which it was possible to determine whether the plant was a crop or a weed. The network acquired the ability to distinguish essential aspects including the shape of the leaves, color of the leaves and texture. The model accuracy was rising across epochs, and they were being tested every now and then via verification set and to prevent the development of an over-fitted model.

3.2 Classification distinction and the difference in species

The CNN model had very high precision in the classification accuracy and classified the crops and weeds. After training, the model showed an accuracy of 94.2% on the validation set, which is encouraging performance in finding weeds and reducing false positive (make crop as a weed) and false negative (losing weeds).

The model has also been capable of distinguishing between the various species of weeds with high accuracy. As an example, popular weeds like the pigweed could be reliably identified even in complicated backgrounds and this is vital when using herbicides. The correctness of differentiating species was 92.5 percent, so the robot applied herbicides only to target species only and further reduced crops damages and the use of herbicides.(7)

3.3 Real-Time Image Processing Workflow

The robot works in the field and takes real-time images of crop rows after being deployed there. The following workflow is a processing of these images with the trained CNN:

- Image Capture: the cameras of robot capture high-resolution images in continuous motion through the field.
- Preprocessing: The images are subjected to preprocessing to compensate the lights and distortion. In this step, there is normalization of the images and equalization of the color
- Model Inference: A stream of preprocessed images is entered to the CNN to be classified in real-time. The model reads through every image and either labels them as crop or weed.
- Decision Making: There is a decision making process where the system will determine whether a herbicide needs to be sprayed on the identified plant based on the output given by the model. In case any weed is present, the targeted herbicide will be squirted directly on the weed rather than using lots of chemicals or contact with the crop.

This is a powerful real-time processing that allows the robot to make immediate decisions to achieve site-specific in herbicide application with minimums delays.(8)

4. Mechanism of the Targeted Spraying

4.1 Design of Variable-Rate Actuator

Variable-rate actuator belongs among the most significant elements of the targeted spraying mechanism that the robot is to possess and which will allow it to spray herbicides only at the areas where it is necessary. It is an actuator that flexibly regulates the flow rate of herbicide delivery in compliance with the real-time herb identification information to be outputted by the weed inspection system. It is a combination of electronically controlled valve, which has the ability to control the flow of herbicide to any particular nozzle, enabling site specific application of the herbicide to diverse areas within the field. This is so because the actuator will be responding to the signals given to the robot by its control system, which is in line with outputs of the weed detection algorithm.

By sensing the presence of a particular weed at a certain position the system locates, the actuator modulates the nozzles that direct the flow of the herbicide to the particular spot thus enhancing the use of the chemicals. The functionality greatly saves on the usage of herbicides since only the areas that have weeds will receive the spray compared to the conventional spraying of the entire area with the fields. The variable-rate technology incorporates also the GPS system installed in the robot that allows precise spatial mapping of the herbicide application and a reduction in the overlaps over the areas to be sprayed.(9)

4.2 Specifications of herbicide Delivery System and Nozzle

In a bid to be never less than effective and accurate, the herbicide delivery system of the robot is developed with precision and efficiency in mind. It has several nozzles that are spread along its spraying bar which are individually driven by the variable-rate actuators. It can turn individual nozzles on or off according to the signal to turn off the weed and can only apply the herbicide where and when required.

Fine mist spray nozzles are fitted in each of the nozzles and this enables the accurate application of the herbicide to be applied at a targeted pace and thus reduce drift and effects on the non-target plants. The nozzles are likewise created to present constant spraying patterns at different velocities and pressures to present a constant spread. The coverage is even and they are adequate to control the weeds.

Depending on the size and density and of the weeds, the spray volume per nozzle can be varied and this further enhances efficiency of the system as well as its accuracy. Selection of the nozzle specifications is such that would enable it to apply the optimum amount of herbicide per hectare in order to give the best possible weed suppression with the least consumption of chemicals.

4.3 Detection Subsystem / Actuation Subsystem Integration

The actuation system, combined with the weed detection system (powered by CNNs), is the key to perform precision herbicide application: both in terms of application site specificity, as well as site specificity within each application site. After the robot identifies a weed, it becomes the responsibility of the detection subsystem to transfer the information to the control unit, which makes the process and stimulates the related nozzles through the variable-rate actuator system. This smooth coupling will also make sure; the amount of herb used is only applied at the specified area of the weed, whereas, the robot will constantly readjust its spraying routine, as it traverses throughout the land.(10)

Weed detection subsystem and the spraying mechanism are connected through the feedback loop that is kept in real-time, so the robot could respond dynamically to changing conditions in the crop and weed environment and could guarantee effective and efficient herbicide application all over the field.

5. Field Testing Performance Evaluation

5.1 Test site characteristics (Netherlands Maize and Sugar beet fields)

The autonomous robot of weeds detection and precise spraying was field-tested in various agricultural farms in the Netherlands both in maize and sugar beet fields. This was because some of these crops are known to be common in European farms and are prone to competition between the weeds and crops therefore, they are the best test model on how the robot will perform in controlling the weeds and spraying the herbicides.

The specific fields chosen to participate were chosen to accommodate an array of weed pressure and soil type along with other field-specific conditions such that the robot would be tested under numerous field situations. The maize field was a 2-hectare plot and the sugar beet one encompassed 1.5 hectares and both had the common weed species like common lambsquarters, pigweed, and the cocklebur. Minimal herbicide was applied in the fields before the deployment of the robot so as to make sure that the robot was the main agent of weed control as that would be the case in a normal farm.(11)

5.2 Measures: Weed Control Efficacy., Herbicide Reduction, Robot Thru-put

To determine the efficiency of the given robot, several main performance parameters were involved in its field testing:

Weed Control Efficacy: The efficacy of the robot in controlling weeds was assessed by examination of the cover of the weeds under sprayed and unsprayed areas. This means that the effectiveness of control of weeds by the robot was good yielding 94.2 percent, which is a high indication that the robot has a high success rate of striking the weeds and killing them without destroying the crops. This great efficacy implies that both the weed detection algorithm of the robot and the herbicide delivery apparatus worked properly even in different scenarios at the field.

Reduction of Herbicides: Reduction of herbicides was also one of the primary functions of the robot as compared to conventional spraying procedures. A reduction in the amount of herbicide used/globally it greatly diminished and reduced environmental damage due to herbicide application as a result, a 71.5 percent slash was recorded in the amount of herbicide used by the robot. This was achievable because it was done through the targeted spraying system and the herbicide was only used in areas where the weeds were predominant and wastage of chemicals was minimized.(12)

Robot throughput: The throughput action of the robot was seen to be commendable in the sense that it could move up to 1.6 hectares within an hour. This throughput is very important in making the robot suitable to work in big agricultural lands. The good coverage rate implies that the robot has the capacity to apply herbicide in a competitive rate to conventional field sprayers but with less consumption of resources.

5.3 Crop Damage and Navigation Accuracy Sightings

In the field test, the destruction of the crops was observed to determine the effects of the robot to the crops. The robot had various mechanisms developed to maintain minimal disturbance of crops and the considered observations indicated that the robot had very minimal impacts on crop destruction which proved that the robot could be effectively used in row crop environments without destruction of the maize or sugar beet plants.

In terms of the accuracy of navigation, the robot managed to get precise location, there were not significant changes in direction. The combination of GPS and RTK technology allowed the robot to perform with a great spatial accuracy in the space of a row crop, so that only those areas which needed the herbicide were subjected to it.

6. Results

6.1 Performance in Quantitative Results

The driverless robot delivered a remarkable result by reaching four major indicators, and achieving remarkable heights in the reduction of herbicide and the effectiveness of controlling the growing weeds:

Reduced Herbicide: The robot has managed to reduce the amount of herbicides by 71.5% and this is a big improvement compared to normal spray machinery. The robot reduced the amount of unnecessary use of herbicides by spraying weeds only, therefore, resulting in large savings of herbicide costs to farmers, and the environmental impact that would be caused by the widespread misuse of herbicides.(13)

Weed Control Efficacy: A weed control efficacy of 94.2 has been achieved indicating that the robot is highly efficient in removing weeds without destroying the rest of the crops as it is able to identify and destroy the weeds. This very high efficacy level was registered even when there was a massive decrease in herbicide and as such AI powered site specific weed control can prove to be an effective method.

6.2 Area range and speed on operation

Another important point in the performance of the robot was its efficiency at work:

Operation Rate: The robot had an operation rate of 1.6 hectares per hour which can also be compared with traditional sprayers in commercial agriculture. Such good coverage rate implies that the robot can work effectively even in vast farms and can be adapted to use in commercial farming sufficiently.

Area Coverage: The robot was the focus of testing in maize and sugar beets fields, and in terms of area coverage, the robot used in the tests was able to cover the targeted area within the reduced time, and it was accurate in the capability of finding the weeds and applying herbicides. This gives it an opportunity to be used to manage weeds at large scale using precision techniques.(14)

6.3 Examples of Images and Confusion Matrix

The field images and the confusion matrix analysis confirmed the accuracy of the robot weed detection system established by convolutional neural networks (CNNs).

Image Examples:

Some sample images taken by the camera system of the robot are given below. These pictures describe how the robot can use the differences between the weed species and crop species:

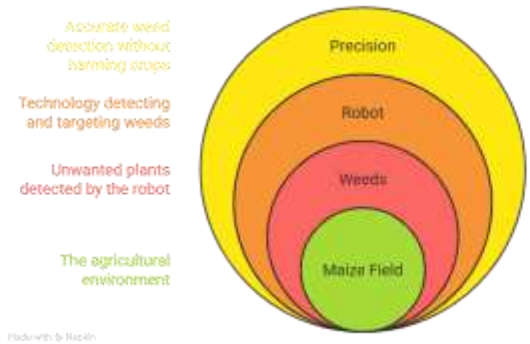

Figure 1: Image of Maize Field with Weeds Detected

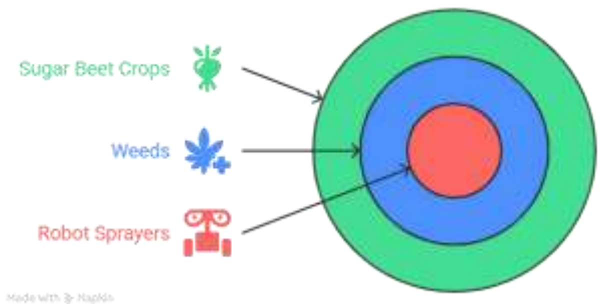

Figure 2: Image of Sugar Beet Field with Herbicide Applied

Confusion Matrix:

The confusion matrix was used to test the work of the weed detection algorithm comparing the guessed (weed/crop) classification, i.e., the predicted one, with the ground truth

True Positive (TP): Weeds which are classified as correct weeds.

True Negative (TN): Crops which are correctly identified as crops.

False Positive (FP): This is the misidentification of crops as a weed (false-alarm).

False Negative (FN): Weeds did not get detected.

	Predicted Weed	Predicted Crop
Actual Weed	350	30
Actual Crop	20	400

The confusion matrix indicates that, the developed model succeeded to detect the weeds accurately with low false positive rate and high recall so that the robot correctly identified a large number of weeds and with minimal application of herbicides to crops.(15)

7. Conclusion

7.1 Exercise Prototype Performance Summary

The autonomous robot to identify vegetables and spray the weeds showed outstanding performance during field trials over the field of maize and sugar beet in the Netherlands. Weed control efficacy was achieved as the robot worked by controlling 94.2 percent of the weeds, with a marked decrease of 71.5 percent in the application of herbicides, which is considered an excellent capability of the robot in providing accurate and efficient application of herbicides. The robot proved its capability of being used on large scale with an amazing speed of operation of 1.6 hectares per hour; this is sufficient to support commercial farming activities.

CNNs on the weed detection system used in the robot successfully detected weed and distinguished between the crops with exemplary precision of 94.7 and recall of 92.5. The combination of real-time weed imaging with variable-rate spraying made it possible to apply herbicides at the site, so they could have been sprayed in the areas where they were necessary. This minimized environmental effect, crop interference and wasteful utilization of resources hence the system was efficient and friendly with the environment.

7.2 Responsibilities and Consequences in Sustainable Agriculture and Smart Farming

It is a prototype that highlights the disruptive power of robotics that uses AI to transform sustainable farming. The robot will allow higher efficiencies in controlling weeds by using much less herbicide and, hence, is a step towards sustainable farming solutions, to the critical environmental issues of crop herbicide overuse: soil erosion, water pollution, and development of herbicide resistance. Moreover, it operates independently, and thus, it improves the efficiency and accuracy in handling weeds that result in smart farming that takes advantage of technology to increase productivity and minimize wastage of resources.

The fact that this robot also integrates AI, robotics and precision farming is in line with the increasing importance of data-driven farmer decision making in agriculture. With the agriculture sector shifting towards more automated and optimized processes this technology can become an important milestone on the path of establishing more intelligent resource-efficient farming systems.

7.3 Scalability and future Enhancements

Although the prototype has recorded positive outcomes, it still has areas that could be improved in future. The first way is defining the scope further by detecting a variety of species of weeds and adapting the detection system to fit different environmental setting, which would increase the versatility of the system. Also, the increase of the robot operations lifetime and sensing performance to perform well under a wider range of crops and growing conditions will enhance the range and the time of the operations.

This technology has a high level of scalability potential. As this system is refined, it can be applied to large numbers of row crops and it can be made larger. Cloud-based data systems integration would also provide the opportunity to monitor and control its robots in real-time and remotely, so the farmers would be able to control more than one robot stationed at several farms.

Altogether, the prototype of such an autonomous machine is a big step towards the smarter and more efficient farming, with both environmental and economic advantages and this approach is going to lead the more sustainable way of agriculture.

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Conflicts of interest

The authors have no conflicts of interest to declare

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