International Conference of Agricultural Engineering
AgEng 2014 Zurich 6–10 July

Ref: C0612

The CROPS agricultural robot: application to selective spraying of grapevine's diseases

Roberto Oberti, Massimo Marchi, Paolo Tirelli, Aldo Calcante, Marcello Iriti, Dept. Agricultural and Environmental Sciences-DiSAA, Università degli Studi di Milano, via Celoria 2, I-20133 Milano, Italy

Marko Hočevar, Faculty of Mechanical Engineering, University of Ljubljana, Aškerčeva 6, SI-1000, Ljubljana, Slovenia

Joerg Baur, Julian Pfaff, Christoph Schütz, Heinz Ulbrich, Institute of Applied Mechanics, Technische Universität München, Boltzmannstr.15, D-85748 Garching, Germany

Abstract

In current viticulture, grapevine's protection is obtained by uniform spraying applications repeated according to a regular calendar. This homogenous and continuous approach to crop protection can easily results in more than ten or fifteen treatments per season in several grapevine-growing areas. Nevertheless, rather than being uniformly diffused, primary infections starts from localized discrete foci. There are then evident potential benefits connected to the development of a system able to detect initial infection foci and target treatments on them instead of the current homogenous and unselective sprayings. This would indeed inhibit or decrease the spread-rate of the infection to wider patches in the vineyard, while enabling significant reduction in use of pesticides.
Within the UE-project CROPS (Clever Robots for Crops), a modular and multifunctional agricultural robot system for specialty crops was developed and one of its applications is selective spraying of disease foci.
The robotic system set-up devoted to this task integrates a six degrees of freedom manipulator, an optical sensor system and a precision spraying actuator. The paper will describe the requirements of the system and its components and it will discuss the results obtained in experiments of selective spraying. As case study, powdery mildew (Erysiphe necator) on grapevine is considered, being one of the major diseases for this specialty crop.
The automatic detection and selective spraying of grapevine canopy areas which exhibit disease symptoms are based on optical sensing feedback, while the precision spraying end-effector is positioned by the robotic manipulator to selectively and accurately apply pesticides solely to disease foci. Optical disease detection and localization is based on on-the-go processing of images sensed by a multispectral (R-G-NIR) camera which inspects the entire structure of the grapevine canopy.
As end effector on the manipulator arm, a precision spraying actuator is used. It is composed by an axial fan with a flow straightener and an axially mounted spraying nozzle. The sprayer can deliver an air-carrier flow with an adjustable velocity, producing a circular spraying pattern of a constant diameter of 0.15 m over a wide range of spraying distances (0.5 – 1.5 m). A first set of experiments was conducted in a greenhouse, where vineyard canopy conditions were recreated by aligning plants of grapevine grown in pots. Within the recreated canopy, diseased plants with different levels of disease symptoms were used as targets of automated selective spraying performed by the agricultural robot. The results of these experiments are discussed in view of a possible intelligent, close precision crop protection framework.

Keywords: automation, robotics, disease detection, precision crop protection

1 Introduction

In current farming practice, pesticides are typically applied uniformly to the fields. This, despite several pests and diseases exhibit an uneven spatial distribution, with typical patch structures evolving around discrete foci, especially during early stages of development. Grapevine crop is not an exception, and in current viticulture practice fungicides are applied uniformly through the vineyard according a spraying calendar, commonly based on regular and frequent fungicide applications, more rarely triggered by scouting or experts decisions. For powdery mildew (*Erysiphe necator*) and downy mildew (*Plasmopora viticola*), the two major grapevine fungal diseases, this continuous protection approach can easily result in ten to fifteen treatments per season, often at application rates of 500-1000 dm^3/ha each, in some of the most advanced wine-producing regions worldwide.
Pesticides are recognized to play a major role in environmental pressure and production costs of agricultural activity, as well as in public concerns about healthiness and wholesomeness products. There is then an increasing interest in developing suitable techniques and equipment able to selectively target the application of pesticides where and when needed by the crop, with the aim of preventing or inhibiting the establishment of the infection and its epidemic spread to the whole field.
The recognised need of an increased precision, selectivity and intelligence in some agricultural operations, combined with growing labor costs, promotes the research on applications of advanced automation. Since crops require different cultivation operations with a huge variety of combinations in parameters, only a highly modular and reconfigurable robotic system suitable for different specialty crops (grapes, sweet-pepper, apples) as well as for multiple tasks (spraying, selective harvesting), can achieve high enough utilization rates.
The main task of UE project CROPS (www.crops-robots.eu) is to develop, optimize and demonstrate a multipurpose, modular and lightweight manipulator able to cope with these specific requirements. The adopted approach it's clearly different from that of other research groups which used non-modular and heavy standard industrial manipulators (e.g. Baeten et al., 2008; Katupitiya et al., 2008) or which focus on one specific fruit and purpose (e.g. Guo et al., 2010; Kitamura and Oka, 2005).
One of the challenging applications of the new CROPS manipulator is the selective, intelligent targeting of pesticides application on disease foci or on susceptible areas of the crop plants.
Among possible sensing technics for disease symptoms detection, proximal optical sensing has specific characteristics especially relevant for field applications on grapevine and other specialty tree-crops. In particular, proximal sensing can inspect the vertical structure of the canopy, allowing for potential on-the-go detection of early symptoms even at centimeter/sub-centimeter scale.
The possibility to optically detect disease symptoms relies on the modifications in the plant tissue induced by the pathogen and, in turn, in the changes of optical properties of the canopy. Beside disease-specific pigmentation, the main optical effects of plant diseases are associated to spectral absorption bands of chlorophyll, where tissue degradation induced by pathogens is especially emphasized.
As case studies we consider here the fully automatic detection, localization and selective spraying by the robotic actuator of powdery mildew symptoms in grapevine canopy, and this paper reports some of the first results obtained in a set of greenhouse experiments aimed to selectively and accurately apply pesticides solely onto infection foci.

2 The CROPS robot system

2.1 The robotic manipulator

The manipulator was designed for different agricultural applications, especially for selective harvesting of different products and for precision spraying. The selective harvesting task has the highest requirements on the dexterity and accuracy in positioning of the end-effector tool. Thus, this application was the basis for the kinematic and mechatronic design, resulting in a nine degrees-of-freedom (DoFs) manipulator. For the precision spraying application, the end-effector must be roughly positioned at a distance of 0.4 – 0.6 m in front of the canopy and has to deal with a canopy wall about 0.9-1 m in height. Since the sprayer is rotationally symmetric, only the rotations around the vertical and frontal axis are relevant.

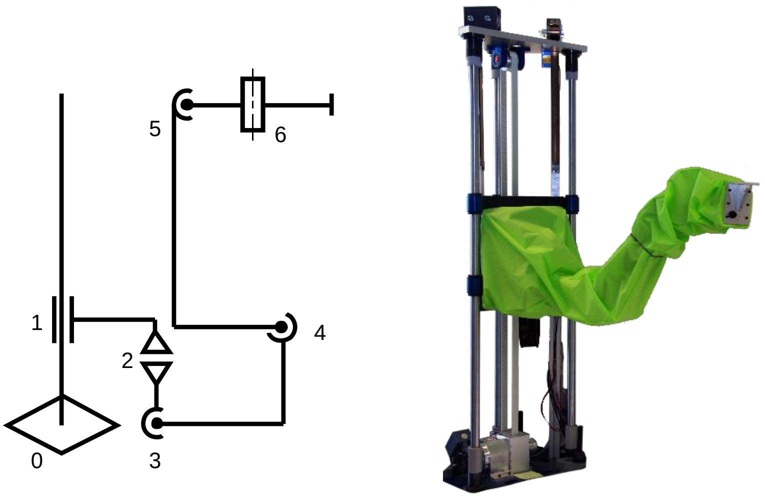

Fig. 1A. Left: six deegres of freedom kinematic scheme of the manipulator in spraying configuration. Fig 1B. Right: manipulator system with waterproof cover protection for spraying operation.

Due to the modular design, the nine DoFs manipulator when used for spraying can be reconfigured to a six DoFs manipulator (Figure 1A) which is more suitable for this application. Furthermore, the end-effector should be able to spray on a target area from several directions to improve the spray coverage. Another requirement for this application is the usability of the arm under the given conditions, meaning that the parts of the manipulator, especially the electronics, have to be protected against liquid droplets.
For having the manipulator ready to work under greenhouse conditions, an external flexible cover to protect the robot against spray droplets. The protective cover is made by a polyoxymethylen tissue shaped as a tube which can be wear on the arm.

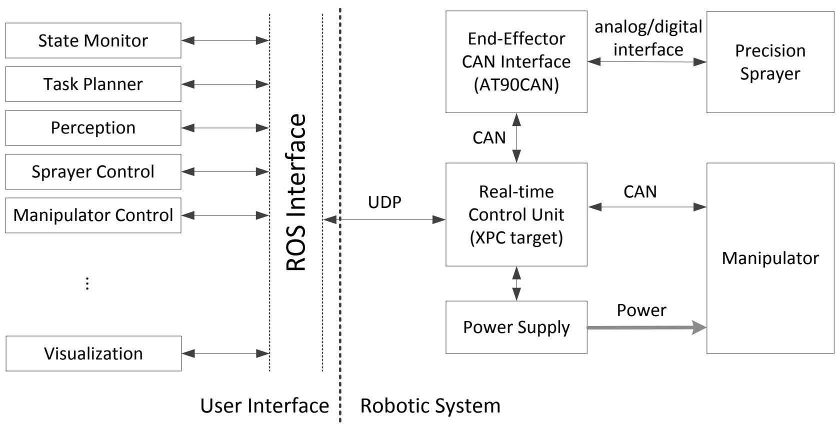

Fig. 2 Hardware and software architecture of the robotic manipulator

A microcontroller interface board (Atmel® AT90CAN32) which provides several digital and analog IO’s for various end-effectors (precision sprayer, apple gripper, and sweet-pepper fruit removal unit) as well as a CAN interface to the manipulator real-time control unit was designed. For the positioning, the target coordinates of the sprayer end-effector-center-point are sent to a real-time control unit via the ROS interface (cf. Figure 2), as well as the fan speed and nozzle actuation of the precision sprayer are controlled by simple ROS messages.

The inverse kinematics is computed by the real time control unit at velocity level (Siciliano, 2009). To avoid instability of the computation close to kinematic singularities, a configuration dependent damping factor is added. This results in a stable, but less accurate solution of the inverse kinematics close to kinematic singularities. The computed joint trajectory is than sent to the low-level motor-controllers of manipulator in each time step.

2.2 Disease detection

Disease sensing in CROPS encompasses a variety of approaches, but multispectral imaging in the red, green, NIR channels (RGNIR) was the detection approach oriented to the final application. The used sensor was a three-CCD multispectral camera acquiring 1912x1076 pixels, 8 bit images in the three spectral channels green (540nm), red (660nm) and near infrared (800nm); in addition an RGB color camera was used mostly for a visual documentation of the scene. The sensors rig was mounted on a two degrees of freedom cartesian sliding frame, allowing for adjusting the sensing position in height (z) and in distance from the canopy (x).
During the experiments the cameras position was kept at a constant height z= 1.4 m, and at an average distance from the canopy wall x = 1 m. The area imaged was about 1.0x 0.5 m, resulting in a spatial resolution of 0.5 mm/pixel approximately.
Halogen light panels providing diffuse illumination of the imaged area were mounted on the sides of the sensors rig.
In order to allow pixels intensity normalization in each of the three spectral channels and to improve data acquisition repeatability at different measurements dates, reflectance standard panels (Spectralon 20%, 50% and 99%, Labsphere, USA) were kept at in a fixed on the border of the field of view of the cameras by a frame holder.

Fig. 3. The CROPS disease sensing system used in field and greenhouse conditions is based on a multispectral R-G-NIR camera; diffuse illumination of the imaged canopy is provided by natural light (through diffusing shield) in outdoor conditions and by halogen light panels in indoor measurements; reflectance standard panels are kept in the field of view to allow spectral intensity normalization and data acquisitions repeatability.

The disease detection algorithm aims to enhance and capture the sharp changes in reflectance (grey pixel levels) in green and especially red channel, due to localised breakdown of chlorophyll in the infetcted tissue which results in a generalised increase in spectral reflectance in the visual range. These specific optical changes were then used for the automatic detection of symptoms.
To this aim the basic architecture of the algorithm is based on two parallel classification processes: i) a pixel-based classification according to computed spectral indexes, and ii) an area-based classification based on local gradient of grey values. Finally, the results obtained

by the two parallel methods are combined to obtain a disease symptoms map in the processed image. For the pixel level classification, rather than using the raw values in the image channels, a pair of selected spectral indexes are computed to enhance discrimination between healthy and diseased areas:

$$I1 = \frac{\mathrm{Red} * \mathrm{Green}}{NIR^2} \quad (1)$$

$$I2 = \frac{\mathrm{Red}}{\mathrm{Red} + \mathrm{Green} + NIR} \quad (2)$$

These indexes are designed to capture the reflectance variations in either red or green channel, or a combination of both, related to chlorophyll absorption band which is especially expected to respond to local tissue degradation linked to a pathogen attack. Specifically, I1 and I2 are expected to give significantly lower grey values for healthy pixels compared to those obtained for pixels in diseased areas. Indeed, classification based on (I1, I2) combinations appears quite sensitive to the disease symptoms, also at early stages, but also prone to significant false positive detections (i.e. non diseased areas classified as diseased). This was found to be especially related to specular reflections on glossy leaf tissue and to specific structures as leaf veins or young, green branches. To reinforce the classification robustness, a local gradient method searches for homogeneous areas in grey level and evaluate the differential contrast between the neighborhood and the candidate areas as detected by aggregation of pixels classified as disease according to (values I1, I2). The local gradient algorithm operates on the normalized red channel image, that is on I2(x,y) map as defined by Eq.(2). To this aim the algorithm searches for peaks in I2 values in the index map, and from each detected peak it performs a region growing to identify an homogeneous area surrounding the peak point. A contrast ratio with neighboring areas is computed and used as a disease probability measure, since disease symptoms exhibit rather sharp changes in I2 value, while false positive generally tend to have smoother changes.
After the two parallel processes, the algorithm fuses the results obtained by pixel-level classification and by the local gradient method and it retains binary regions with a combined probability above a fixed threshold.
These binary regions are assumed as disease symptoms present in the canopy area in the multispectral image.

2.3 The sprayer end effector

The sprayer end effector consists of an axial fan as airflow generator with airflow straightening device, an airflow duct, a pesticide nozzle with anti-dripping device, an electrical connector for power supply and control signals, all enclosed in a plastic/alluminium chassis. The sprayer end effector was designed with the main goal of performing precision spot spraying of small patches of infected areas.
In operation the end-effector has to be connected to a pumping station and a pesticide formulation tank placed at the base of the manipulator. The pesticide delivery flow-rate ranges from 15 ml/min to 50 ml/min, depending on the selected nozzle tip. The one used during the experiments has a flow-rate of 30 mL/min at a pressure of 4 bars, with a full cone pattern of 30° and an average diameter of spray droplets of about 150 µm.
The fan features PWM control for rotational speed, allowing to set the air-carrier flow velocity from 5 to 30 m/s. As overall result, the sprayer end effector delivers a circular spraying pattern of a constant diameter of 0.15-0.2 m over a wide range of spraying distances (0.4 - 1.5 m). The control signals of fan-speed and of nozzle operation are provided to the end effector via ROS.

3 The greenhouse experiments

3.1 Plant material preparation and canopy setup

The selective spraying concept was tested in a session of greenhouse experiments conducted in 2013 on grapevine canopy with localized symptoms of powdery mildew, one of the two major diseases for this specialty crop.
To this aim in spring 2012, 180 plants of grapevine cv Cabernet Sauvignon were propagated from wood, and nursed in 30 cm diameter pots to grow by maintaining greenhouse environment under controlled conditions. Plants were pruned so that they reached full development stage for the off-season experiment, when the CROPS manipulator was made available after field experiments in other sites considered within the project.
A subset of grown grape plants was inoculated by brushing Erysiphe necator (the pathogen of powdery mildew) conidia onto the upper face epidermis of healthy leaves in order to induce powdery mildew infection. The infected plants were nursed in a separated greenhouse room where favourable environmental conditions for disease development were maintained.
For purpose of experimenting the selective spraying system, the plant material was arranged in a greenhouse setup in order to simulate vineyard canopy conditions by aligning healthy grapevine plants in pots on tables (Fig.4). Within the recreated canopy wall, diseased plants with different levels of symptoms were positioned in order to simulate the presence of localised disease foci within healthy vegetation, representing the actual targets of selective spot spraying.

Fig.4. Example of grapevine plants setup to recreate a vineyard canopy wall in greenhouse conditions. Among aligned healthy plants, infected plants with different levels of symptoms were positioned to simulate localised disease foci (in red) within healthy vegetation.

Different replicates of grapevine canopy plot (5 m in length x 1,8 m in height) were obtained by preparing different plants arrangements by substituting healthy and diseased plants with other spare samples and/or changing their position in the line.
Prior to each robotic spraying pass, the canopy plot was accurately monitored by visual inspection by a plant Pathologist. Position, size and intensity of disease foci symptoms were recorded and used for assessing the results obtained with each robotic spraying treatment.

3.2 Robotic system setup and experimental procedure

For the spot spraying experiments session, the disease detection system and the manipulator equipped with precision spraying actuator were integrated on a trailer platform, hosting the PC for data acquisition and real-time processing and the controller of the manipulator. The manipulator geometrical coordinates system was then registered with the coordinates system of the multispectral camera. With this procedure, the position of a point at a known frontal distance X from the camera and having coordinates (yi, zi) in an acquired image, can univocally translated in a vector of coordinates (xm, ym, zm) of the manipulator reference system.
During the experiments, the trailer holding the robotic system was positioned frontally to the recreated canopy and while traveling was kept at a constant distance from the midline of the vegetation. The trailer was moved in front of the canopy wall at steps of 10 cm. At each position a multispectral image of the canopy was acquired and processed in real-time.

The obtained results in terms of presence and position of disease symptoms were written in to a spraying targets queue file. Concurrently, the targets in the queue list identified by previous acquisitions and having a position in the canopy reachable by the manipulator at current trailer standing, were aggregated in single spray spots (i.e. within circles having a diameter of 15 cm). The coordinates of the center of each resulting spray spot were then passed to the manipulator controller through ROS messages. The corresponding targets were assumed treated and consequently removed from the queue list.

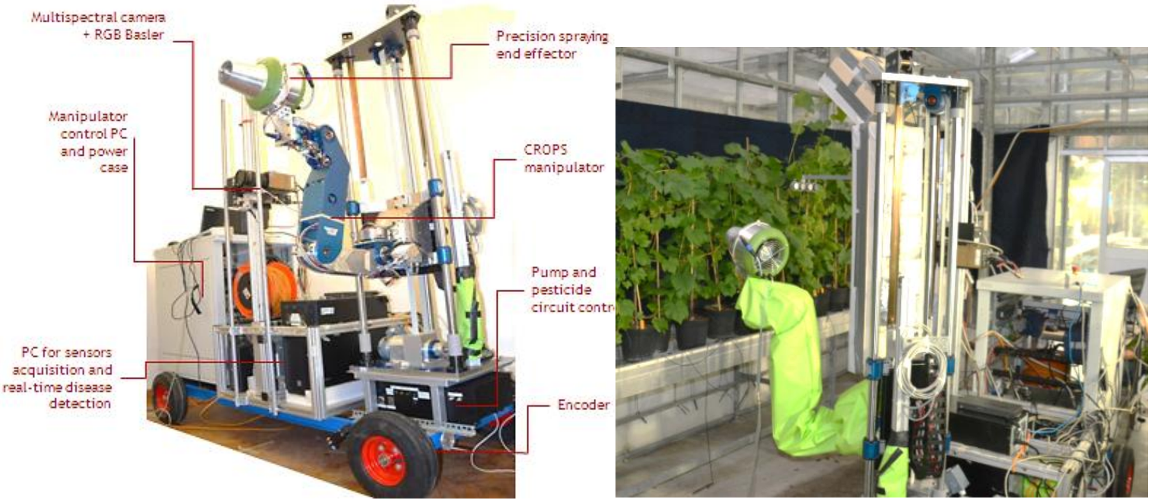

Fig. 5. The robotic setup integrated on a trailer during preparation in the lab (left), and during experiments of selective spraying on grapevine in greenhouse (right).

In order to maximize the homogeneity of spraying deposit and covering of targets, each single spot (i.e. a circular area of the canopy with a diameter of 15 cm) was sprayed from three different directions. For each spot to be sprayed the manipulator was then commanded to bring the end effector in three positions from where the nozzle was operated to deliver one third of the nominal flow (0.5 s on a total of 1.5 s of spraying time). The sequence of three positions was: i) distance from spot's center d= 0.6 m, latitude angle α=30°, longitude angle γ=0°; ii) distance from spot's center d= 0.6 m, latitude angle α=-30°, longitude angle γ=+30°; iii) distance from spot's center d= 0.6 m, latitude angle α=-30°, longitude angle γ=-30°.
With this spraying sequence timing, each identified target received a corresponding application rate of 375 $dm^3/ha_{foliage}$ which is a representative value of current grapevine protection treatments.
When all the targets in queue falling in the workspace of the manipulator at current trailer standing were sprayed, a message of duty accomplished was generated and trailer was then moved by 10 cm to next step.
In order to assess the performance of the automatic disease detection system the algorithm output for each robotic pass was compared with the visual inspection records (position, size, intensity of symptoms) made by plant Pathologist. The final spray deposit on the canopy, and specifically on individual disease foci, was evaluated by spraying a fluorescent dye mixture.

4 Example of results

The operative results obtained with robotic selective spraying of disease symptoms were quantitatively assessed through: a) the sensitivity of the selective treatment, i.e. the capability of covering real targets (fraction of canopy area to be sprayed which was actually sprayed by the robot); b) the specificity of the selective treatment, i.e. the capability of avoiding excess of unnecessary spraying (fraction of canopy area not to be sprayed which was actually left unsprayed by the robot); c) the pesticide reduction of the selective treatment, which expresses the reduction of used pesticide in comparison of a conventional uniform spray distribution operated at the same application rate.

As one specific and illustrative result, figure 5 refers to the first experimental run. The blue chart in figure shows the disease spots (blue dots) as detected by the system and the corresponding sprayings (blue circles) operated by the robot. These results are compared with the “ground truth” in the red chart which shows the disease symptoms (red dots) labelled by a plant Pathologist by visual inspection conducted prior to the robotic pass, and the computed minimal spot sprayings (red circles) necessary to treat all the disease foci. In this specific run (experiment 1) the robot sprayed 25 spots which actually covered all the disease foci. The obtained reduction in pesticide use compared to a conventional homogeneous spraying of the canopy (assuming to adopt the same application rate) was 84% (i.e. only the 16% of amount necessary for conventional treatment was used). For this specific scenario, a potential spraying reduction of 6 % could have been attained by actuating the minimum number of spraying spots necessary to treat the disease symptoms actually detected by the plant Pathologist.

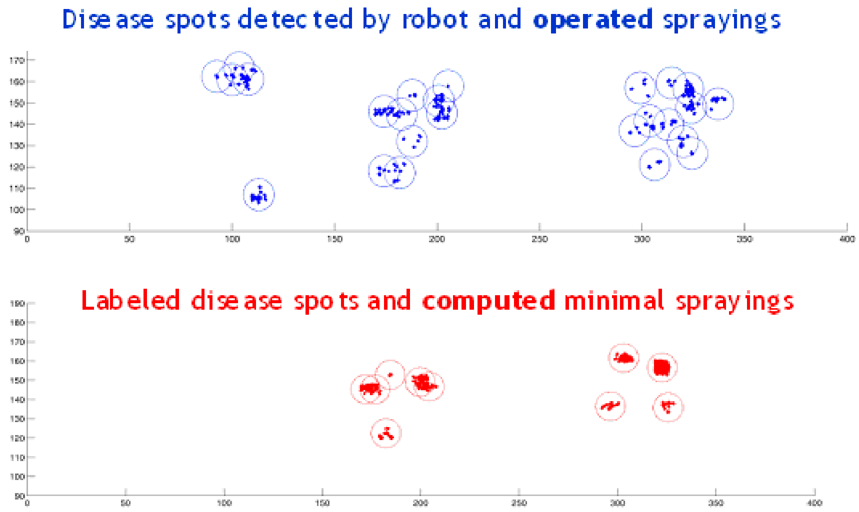

Fig. 5. Above, disease spots (blue dots) detected by the system and corresponding spot sprayings (blue circles) operated by the robot compared to, below, labelled disease spots by plant pathologist through visual inspection (red dots) as estimated by plant pathologist and the computed minimal spot sprayings (red circles) necessary to treat all the disease foci.

An overall analysis of the results obtained in the repeated experimental runs shows that with the current settings of CROPS robot for precision spraying, at least the 85% of the infection symptoms in disease foci sprayed, with a reduction of pesticide-use close to 90% of the maximum potential reduction, given the diseased area specifically considered in the experimental run.

Noticeably, false negatives (undetected disease symptoms) are mostly falling in the surroundings of detected disease areas, hence could be treated anyway by including a conservative safe-border area around the spot spraying targets, which in these experiments was purposely not taken in consideration. Despite this will reduce the potential pesticide savings, it might help to raise the level of acceptance in to real-world cases of robotic close precision spraying application.

Acknowledgments

The CROPS project is funded by the European Commission (GA-246252) under the 7th Framework Programme within the theme “Automation and robotics for sustainable crop and forestry management”