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SYSTEMS ARTICLE

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Design and development of a semi-autonomous agricultural vineyard sprayer: Human–robot interaction aspects*

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Abstract

This article presents the design aspects and development processes to transform a general-purpose mobile robotic platform into a semi-autonomous agricultural robot sprayer focusing on user interfaces for teleoperation. The hardware and the software modules that must be installed onto the system are described, with particular emphasis on human–robot interaction. Details of the technology are given focusing on the user interface aspects. Two laboratory experiments and two studies in the field to evaluate the usability of the user interface provide evidence for the increased usability of a prototype robotic system. Specifically, the study aimed to empirically evaluate the type of target selection input device mouse and digital pen outperformed Wiimote in terms of usability. A field experiment evaluated the effect of three design factors: (a) type of screen output, (b) number of views, (c) type of robot control input device. Results showed that participants were significantly more effective but less efficient when they had multiple views, than when they had a single view. PC keyboard was also found to significantly outperform PS3 gamepad in terms of interaction efficiency and perceived usability. Heuristic evaluations of different user interfaces were also performed using research-based HRI heuristics. Finally, a study on participants' overall user experience found that the system was evaluated positively on the User Experience Questionnaire scales.

KEYWORDS

Human-robot interaction, agricultural robot, user interface design, usability, user experience

1 | INTRODUCTION

Robotics in agriculture is considered to be a *field application domain*, because it has the characteristics identified by Murphy[1]: (a) the robots are subject to unpredictable environmental effects that can impair platform and perceptual capabilities, and (b) robots are primarily extensions of humans doing what a farmer would do in the physical environment. As opposed to industrial robots, which operate in controlled environments, agricultural robots must deal with continuously changing physical environments. Agricultural robots are challenged by several complexities including[2]: (a) moving on unstructured and unpredictable terrain, (b) dealing with highly variable objects (e.g., fruit, leaves, trees) which because of plant physiology and genetics differ in size, shape, color, shading and are located at random non-uniform locations, and (c) working under uncontrolled and volatile climate-related conditions (i.e., wet muddy soil, strong winds, different light/shading settings depending on the sun location or clouds and obstructions such as leaves and branches).

The mainstream direction for robotics in agriculture to date is full automation: developing intelligent agricultural machinery to execute a specific agricultural task (e.g., spraying, harvesting, pruning). Despite the intensive developments, agricultural robots are not yet widespread[3] mainly due to: (a) safety reasons, (b) the robotic technology being still too expensive, and (c) current mechanical and technological limitations related to the aforementioned environmental and plant-specific conditions complicating the development of completely autonomous systems,[4] leading to their limited performance. Thus, one important factor to a more widespread use of robotics in agriculture is its effectiveness. However, a barrier seems to exist, currently at about 85–90% of effectiveness: the best existing algorithms and machinery cannot efficiently harvest[3] or spray[5] more than this percentage of crops.

Figure 1 illustrates the excessive amount of pesticides released to the environment and the exposure of humans to these dangerous chemicals during two widely used spraying approaches (tractor-spraying and handheld spraying) today.

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FIGURE 1 Current methods used for vineyard spraying. Left: farmer on a tractor-sprayer in a vineyard field, Right: farmer inside a greenhouse using a handheld sprayer

Precision agriculture techniques were also applied for spraying orchard trees. Wellington et al.[6] developed automated tree inventory and more precise spraying using probabilistic approaches for interpretation of radar sensor data combined with GPS and generating tree models in an orchard environment. Endalew et al.[7] studied and modeled the effect of tree foliage on sprayer airflow in a peer orchard. They used a 3-D computational fluid dynamics model integrated with a 3-D canopy architecture with a closure model to simulate the effect of the stem, branches, and leaves on airflow from air-assisted orchard sprayers. The developed model was able to show the flows within and around the canopy.

Research on autonomous agricultural robot sprayers has been performed in the past decades.[8] A comparative list with specific results, the plant application, and sensor technology used is presented by Berenstein et al.[5] Berenstein et al.[5] used a grape cluster and foliage detection algorithms for target-specific autonomous robotic sprayer and showed that selective spraying can reduce the quantity of pesticides applied in modern agriculture by 30% while detecting and spraying 90% of the grape clusters. Recently, Guzman et al.[9] presented VINBOT, a robot for precision viticulture. VINBOT is an autonomous mobile robot capable of capturing and analyzing vineyard images and 3D data by means of cloud computing applications, to determine the yield of vineyards. VINBOT estimates the amount of leaves, grapes, and other data throughout the entire vineyard via computer vision and other sensors and generates online yield and vigor maps. Zaidner and Shapiro[10] proposed a data fusion algorithm for fusing localization data from various robot sensors for navigating an autonomous system in the vineyard.

In this paper, a semi-autonomous agricultural teleoperated robot sprayer is introduced. The robot, in addition to whatever pre-programmed operation it can do autonomously, is in communication with a human operator, the "farmer," who intervenes either when the robot asks or when she/he decides to do so. The farmer does not need to be present in the field; for reasons of occupational comfort and safety (as in the case of spraying which is the example discussed here) as well as for reasons of efficiency (as in the case of operating multiple robots in tandem which is not discussed here), the farmer is assumed to be "away." Operating a robot from a distance is often termed teleoperation.[11] Agricultural robot sprayer teleoperation can reduce human exposure to pesticides, thus reducing safety concerns and medical hazards.[5]

Teleoperation introduces the human capabilities of perception, auditory, anticipation, and pattern and motion recognition to a robotic system in the remote worksite. However, humans tend to fatigue, are subject to distraction and not consistent. According to Fong et al.[12] teleoperation can be significantly improved if humans and robots work as partners. At the same time, the human operator must be supplied with sufficient sensory information, in order to be able to form an accurate mental model of the worksite and the surrounding area where the robot is operating.

Humans working collaboratively with robots to accomplish a task, i.e., collaborative control[13] raises research issues of human–robot interaction. Human–robot interaction (HRI) may occur through proximal (direct) interaction or remote interaction. In the latter case, HRI is mediated by a user interface (UI). This paper focused particularly on the aspects of the user interface for HRI, and how it should be designed,[14] in order to be suitable for teleoperation of a mobile field robot while performing agricultural tasks, such as spraying.

The ultimate goal for human–robot interaction is to develop and use efficiently the robots freeing humans from routine or dangerous tasks.[17] Interaction, the process of humans working together with robots to accomplish a goal, emerges from the confluence of autonomy, information exchange, teams, and task shaping.[18] For a fully autonomous robot the interactions may consist of high level supervision and direction of the robot; the human provides goals and the robot maintains knowledge about the world, the task, and its constraints.

In this paper, the design aspects and development processes to transform a general-purpose mobile robotic platform into a semi-autonomous agricultural robot sprayer are presented. Human–robot interaction aspects are detailed. Two such robot systems were developed in the context of consecutive R&D projects; the AgriRobot* and the SAVSAR†. The methodology followed for the design, development, and testing of these two agricultural robot sprayers and their evolvement are presented. The methodology to engineer a semi-autonomous agricultural robot sprayer is presented focusing on the respective user

* https://youtu.be/w3Inq5tBxa8

† https://youtu.be/-zdN8b806b0

interfaces and their evaluation. Experiments performed during the two aforementioned R&D projects are described and the main goals, methods, and findings are presented.

2 | BACKGROUND INFORMATION

2.1 | Teleoperated and autonomous agricultural robots

Teleoperated robots have been successfully used is various contexts, such as in space,[19,20] for medical applications,[21] and in agriculture as well.[22–25] One way to accomplish a high level of situational awareness[26,27] is to allow the operator to view the worksite from an observer's perspective.[28]

Fong et al.[29] explain that remote driving is difficult because of problems in perceiving and evaluating the remote environment, poor attitude and depth judgment, difficulty to detect obstacles, operator workload, and the fact that the robot is operating in a changing dynamic environment. They examined multimodal operator interfaces and semi-autonomous control which have "*proven to be useful*." Specifically they used three options: gesture recognition, haptics, and a personal digital assistant (PDA). The GestureDriver assumed that the operator was in the robot's field-of-view; however they concluded that visual gestures were not as easy. The HapticDriver provided force feedback to the operator once the robot was approaching an obstacle. Its limitation was that it provided 2-D force information. The PDADriver was the easiest to deploy and provided several modes: video, map, command, and sensor which resulted in high usability, robustness, and performance.

In the case of agricultural robot teleoperation, there is a human farmer "behind" the robot, directing the agricultural work from a safe distance and in comfortable conditions, receiving data from robot's sensors and cameras, while directing or supervising it via a human–robot user interface. Semi-autonomous robots, including controlling robots from a distance,[30] provide a promising alternative that could overcome the limitations of fully autonomous robots.

Sheridan and Verplank[31] proposed ten levels of automation that are "*assumed to apply to most man-computer decisions*." Bechar and Edan[23] defined, implemented, tested, and evaluated four basic levels for human–robot collaboration: (1) HO: the human operator unaided, detects and marks the desired target – compatible with level 1 on Sheridan's scale; (2) HO-Rr: the human operator marks targets, aided by recommendations from an automatic detection algorithm, i.e., the targets are automatically marked by a robot detection algorithm, the human acknowledges the robot's correct detections, ignores false detections and marks targets missed by the robot – compatible to levels 3–4 of Sheridan's scale; (3) HO-R: targets are identified automatically by the robot detection algorithm; the human operators' assignment is to cancel false detections and to mark the targets missed by an automatic robot detection algorithm – compatible to 5–7 in Sheridan's scale; and (4) R: the targets are marked automatically by the system (robot) – compatible to Sheridan's 10 level. Analytical[32] and simulation[24,32] approaches demonstrated that collaboration of human operator and robot can increase detection rates and decrease false alarms when compared to a human operator alone or a fully autonomous system. Implementation on an operational robotic sprayer[33] indicated similar improved performance when a human collaborated with the robot.

2.2 | User interfaces and usability evaluation for HRI

An important part of the collaboration which has not been previously addressed in agricultural robotics is the interface design. Conversely, human–robot interaction user interface design and usability evaluation has been studied extensively in other areas such as search and rescue operation robotics.[34–37] Advanced research has addressed several aspects related to interface design.[38–40]

There are several approaches for interface design including the ecological interface paradigm,[41] adaptation of the Unified Modeling Language (UML) a graphical language, for modeling user interfaces for human–robot interaction. Weiss et al.[42] and Keyes et al.[43] presented an iterative user-centered design approach for the development of a new interaction paradigm for the remote control of robots.

Yanco et al.[44] explain that human–computer interaction (HCI) evaluation methods, such as the Goals, Operations, Methods, and Selection rules (GOMS), can be adapted for use in HRI as long as "*they take into account the complex, dynamic, and autonomous nature of robots*." They studied human–robot interfaces to determine what information helps operators to successfully navigate the robots in disaster areas and locate victims. HRI interface design evaluation includes heuristic evaluation[45] and analytical methods like GOMS.[46]

Drury et al.[26] explain why traditional modeling techniques used in HCI differ in HRI: assumptions such as error-free operation on the part of the user and predictable operations on the part of the robot are "unreasonable." Other challenges include the different levels of automation of mobile robots, the varying quality of sensor data, the notoriously non-routine and unpredictable robot operations, and the pointing devices used to move a robot from point A to point B (i.e., using a joystick instead of a mouse). Clarkson and Arkin[45] declared, "*what makes a robotic interface (no matter what the form) effective is no different than what makes anything else usable, be it a door handle or a piece of software*."

Usability refers to whether a system can be used with effectiveness, efficiency, and satisfaction with which specified users achieve specified goals in a particular context of use.[47] A usability issue is anything that can affect the user experience in a negative way. There are many sources of data that can be used to derive usability issues[48] such as user performance data (e.g., task success rate, time on task), verbal expressions of confusion or dissatisfaction, such as from a think-aloud protocol,[49] behavioral/physiological data, e.g., from eye-tracking[50] and reports from usability experts, such as heuristic evaluation.[51]

Nielsen[51] explains that "*Heuristic evaluation is a 'discount usability engineering' method for evaluating user interfaces to find their usability problems.*" In this evaluation usually 3 to 7 experts are sufficient to reliably evaluate the usability of the user interface. Usability issues are often prioritized based on severity schemes[52,53] that consider various factors (e.g., expected impact on user experience, predicted frequency

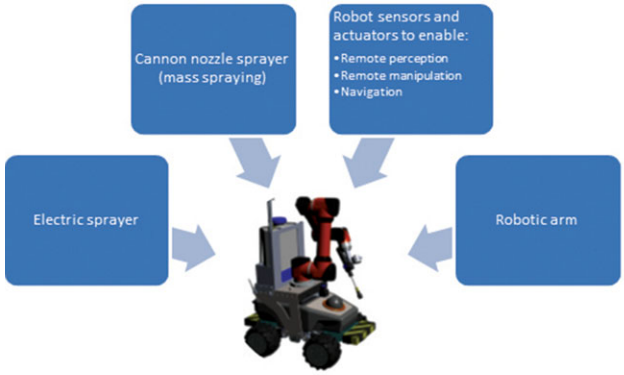


FIGURE 2 Schematic diagram with modules to engineer a mobile robotic platform into a robot sprayer

of occurrence, expected impact on business goals) in an attempt to increase their usefulness for the next design iteration.

Subjective assessment of usability (i.e., perceived usability) can be measured by the post-task 10-item System Usability Scale (SUS).[54–57] SUS is a post-study questionnaire that assesses the perceived usability of a system. It consists from 10 statements to which participants rate their level of agreement on a 5-point scale. Half of the statements are positively worded (e.g., "I would imagine that most people would learn to use this system very quickly") and half are negatively worded (e.g., "I found the system very cumbersome to use"). Based on a formula, a total SUS score is obtained from each user ranging from 0 (negative) to 100 (positive). An overall SUS score for the evaluated system can be obtained by averaging the users' SUS scores. Bangor et al.[58] associated SUS scores with a 7-point grading scale of perceived usability (from worst-imaginable to best-imaginable). Tullis and Stetson[59] compared various post-study questionnaires and found that SUS yields the most consistent ratings.

3 | TRANSFORMING A MOBILE ROBOTIC PLATFORM INTO AN AGRICULTURAL ROBOT SPRAYER

To transform a general-purpose mobile robotic platform into a robotic sprayer, several modules must be adapted and integrated. These modules include the mobile robot platform, an electric sprayer, a robotic arm, and various robot actuators and sensors. The description here is based on two versions of the hardware and several versions of the software of systems developed and implemented, the AgriRobot and the SAVSAR. Figure 2 is a schematic of the most advanced one (SAVSAR).

3.1 | The mobile robot platform

The operational requirements of the medium-sized mobile robot platform to be transformed into an agricultural sprayer were based on experience from previous R&D projects partners' expertise. These include:

- All-terrain mobility (including skid-steering kinematics)
- Navigational capabilities based on odometry, GPS, sonars, lasers, and bumpers
- Climbing angle of at least 45 degrees
- Speed of up to 3 meters per second
- At least 3 hours of battery autonomy
- Payload of ≥ 25 kg allowing a meaningful spraying session
- Sufficient surface to install on it a sprayer tank and/or robotic arm; based on the size of an 18-liter tank, at least 40×65 centimeters is required
- Environment input devices such as cameras and microphones

Table 1 presents the two robot platforms where were transformed to robotic sprayer with their characteristics based on the above requirements.

3.2 | HRI aspects to be considered

The design of the robot's user interface was based on the analysis of user contextual interviews of farm workers and agronomists that pilot tested in the field an initial version of the agricultural robot sprayer.[60] Several HRI-related limitations were identified such as: (a) the lack of peripheral vision, (b) the fact that the operator required a significant amount of time to pan-tilt zoom-in and zoom-out from the main robot camera to identify grapes (targets) to spray, (c) limitations to Bluetooth connection via the PS3 gamepad controller, and (d) illumination of the laptop monitor due to sunlight.

An improved version was designed following informal interviews and documentation of their observations and several modifications on the platform. The new version included a peripheral camera on the back-top of the platform and an end-effector camera on-top of the nozzle canon sprayer. To solve the issue of the distance limit of the PS3 gamepad controller, two approaches were implemented: (a) connecting the controller through WiFi and (b) adding a PC keyboard alternative as input device. To address the issue of sunlight and illumination of the PC monitor two solutions were provided: (a) connecting the output device to digital glasses and (b) teleoperating the robot from inside an office environment.

3.3 | Sensors

The agricultural robotic sprayer should be equipped with sensors for localization and navigation (GPS, IMU), for detecting the targets (grape clusters) and for sensing the environment (vine bushes, stones; using cameras and LASER). The technical characteristics of the sensors and other modules used to transform a general-purpose, medium-sized mobile robot platform into an agricultural robot sprayer are presented in the following.

3.3.1 | GPS

A GPS module provides localization of the robot in the field. This is particularly important in medium and large vineyards so that the operator has adequate information regarding robot position and better control

TABLE 1 AgriRobot and SAVSAR requirements characteristics

Feature requirement	AgriRobot	SAVSAR
		
All-terrain mobility	Yes	
Climbing angle	45 degrees	
Skid-steering	4 high power motorwheels	
Speed	3 meters per second	
Odometry	Encoder on each wheel and a high precision angular sensor assembled inside the chassis	
Battery autonomy	5 hours	
Pan-tilt-camera	Yes	
Additional cameras	Yes	
Electric sprayer	Yes	
Payload capacity	25 kg	65 kg
GPS	No	Yes
Sonar sensor	Yes	No
Laser sensor	No	Yes
Lidar sensor	No	Yes
Inertial Measure Unit	No	Yes
Bumpers	Yes	Yes
Robotic arm	No	Yes

of its whereabouts. Furthermore, the GPS enables the operator to create a pre-planned trajectory to be followed by the robot.

3.3.2 | IMU

An inertial measurement unit (IMU sensors and hardware filter circuitry) plus an Arduino-compatible processor, is part of our solution. The advantage of this all-in-one module instead of just using each of its sensors is that the board merges the data and conducts cross-checking. Furthermore, the information it provides can be used to refine other sensory information such as providing position information like a GPS.

3.3.3 | Cameras

In semi-autonomous and remote teleoperation applications, the operator is not co-located with the robot. To enable the user's remote perception, at least three cameras are needed to alleviate the restricted field-of-view effect[61] and provide the user with HRI awareness.[62] In the experiments reported in the following, we found out that this was true even when the operator was co-located with the robot.

The selected robotic platform provided three on-board cameras: (a) one AXIS P5512 PTZ Dome Network Camera (E-flip, Auto-flip, 100 pre-set positions, Pan: 360°, Tilt 180° and 12x optical zoom and 4x digital zoom, total 48x zoom), (b) one Logitech Sphere Camera with motorized tracking (189° horizontal and 102° vertical), Autofocus lens system, a frame rate of up to 30 fps and a resolution of 1600 by 1200 pixels (HD quality), and (c) an AXIS M1025 HDTV 1080p network camera.

The first camera is located on the front of the robot chassis and provides view to the road ahead and around the robot. The second camera is placed at the back-top side of the robot to enable peripheral vision. A third camera is placed on the end-effector sprayer nozzle to give visual feedback of the spraying area.

3.3.4 | Laser scanners

Two laser scanners should be used one for navigation (on-board) and another one for distance measuring (installed on the robotic arm). The laser scanner is a module that when integrated in the robotic platform can be useful to recognize the space in front and around the robot. In the autonomous mode, the laser scanner module helps the robot to avoid obstacles, such as vine trees, stones, humps and dips as well as humans and animals. In the semi-autonomous mode, the laser scanner is used to halt the robot when it comes across an obstacle; this ensures safety. In that way we can ensure that robot or humans/animals will stay safe. In addition, a 360 degree 2D laser scanner can perform 360 scans within a specified range.

The Lidar Sensor produces a 2D point cloud data that can be used in mapping, localization, and object/environment modeling. This is particularly useful when an environment model is required that—together with the cameras and the laser scanner—allows an operator to have all the information needed regarding the field environment thus controlling even better the robotic platform movement and the rest of its actions. For example, Walklate et al.[63] in a review of different models of spray volume deposition that were developed to enable the adjustment of pesticide output from an axial fan sprayer to suit different apple orchards, found that the best correlation was obtained with a length-scale proportional to the tree area density and this accounted for 78% of the variation in the measurements. The calculation of the tree area density parameter relied on the availability of LIDAR measurements.

3.4 | End-effectors

Following the field experiments with the AgriRobot sprayer (mass spraying), participants (agronomists and farm workers) identified a limitation with respect to the robot's ability to spray selectively identified grape clusters (targets). The canon nozzle sprayer is stabilized and cannot move in any direction. A number of participants suggested including a movable nozzle sprayer. The improved version of the selective targeted spraying robot was therefore designed to include a robotic arm with six degrees of freedom.

3.4.1 | Mass spraying

Several modifications and adjustments are required in order to install a sprayer on the top cover of the mobile robot chassis. Initially, a Serena electric sprayer was used. A metallic case was custom-built to hold the sprayer tank. The mass spraying was achieved with a stable nozzle cannon. Then, a Modbus IO was installed so that the electric sprayer was enabled to send the on/off switch command to the robot. The Modbus IO is an Ethernet communication that has 8 digital inputs and 4 digital outputs which was connected directly onto the robot's battery. To control the On/Off switch of the sprayer one of the relay outputs was used. This switch is controlled through a PS3 gamepad button or the keyboard (spacebar).

3.4.2 | Selective targeted spraying

Based on our experience from the Agrirobot project and user needs captured with the thinking aloud protocol during field experiments selective targeted spraying was implemented for the follow-up SAVSAR project. The Summit* XL HL platform with a robotic arm in addition to the sprayer tank was used. The installed robotic arm is the OUR-1, a low-cost, light-weight, industrial Open Unit Robot†. The manipulator has six joints and corresponding degrees of freedom. The OUR-1 consists of the robot base, a shoulder, an elbow, and three wrist joints. There is also a teach pendant which can be used to control the rotational motion of each joint for moving the tools on the end-effector (nozzle) to different poses. The teach pendant also provides visualized operation and a programming interface; technicians can test, program, and simulate the robot manipulator through the teach pendant.

3.5 | The user interface

An iterative user-centered design process was followed in the context of two research and development projects (AgriRobot and SAVSAR) in order to design and develop the robot's teleoperated UI (see Fig. 3). Figure 4 presents the final version of the user interface of the AgriRobot and SAVSAR systems.

In the following, the different components of the final version of the user interface (see Fig. 4, SAVSAR UI) are elaborated. This design of the user interface was based on recommendations from Adamides et al.[14] related to the following factors: (1) Platform Architecture and Scalability, (2) Error Prevention and Recovery, (3) Visual Design, (4) Information Presentation, (5) Robot State Awareness, (6) Interaction Effectiveness and Efficiency, (7) Robot Environment/Surroundings Awareness, and (8) Cognitive Factors. Furthermore, empirical findings from both lab and field studies (see Section 5) were taken into consideration during the user interface development.

1. **Sonar sensor indicators (front: left, center, right, and back: left, center, right)**: The sensor indicators are represented by a black bar which is colored green when the distance of the robot from the obstacle is greater than 2 meters, yellow if it is between 1 and 2 meters, and red if the distance is less than a meter. In the last case, additional auditory feedback (beep sound) is provided. The length of the bar shortens as the distance from the obstacle increases. Furthermore, the actual distance in cm/m is shown inside the bar. The aforementioned UI components are associated with design guidelines 2 (Error Prevention and Recovery), 4 (Information Presentation), 7 (Robot Environment/Surroundings Awareness), and 8 (Cognitive Factors).
2. **Battery sensor indicator**: This indicator presents the battery level status. It is presented as a horizontal bar that is colored green when the battery is full (100%), yellow for battery level between 75% to 25%, and red when the battery level goes below 25%. There is also a text label with the actual percentage on the battery-bar. Additionally, the length of the bar is proportional to the percentage level of the battery. The aforementioned UI component is associated with design guidelines 5 (Robot State Awareness) and 8 (Cognitive Factors).

* http://www.robotnik.eu

† http://www.our-robotics.com

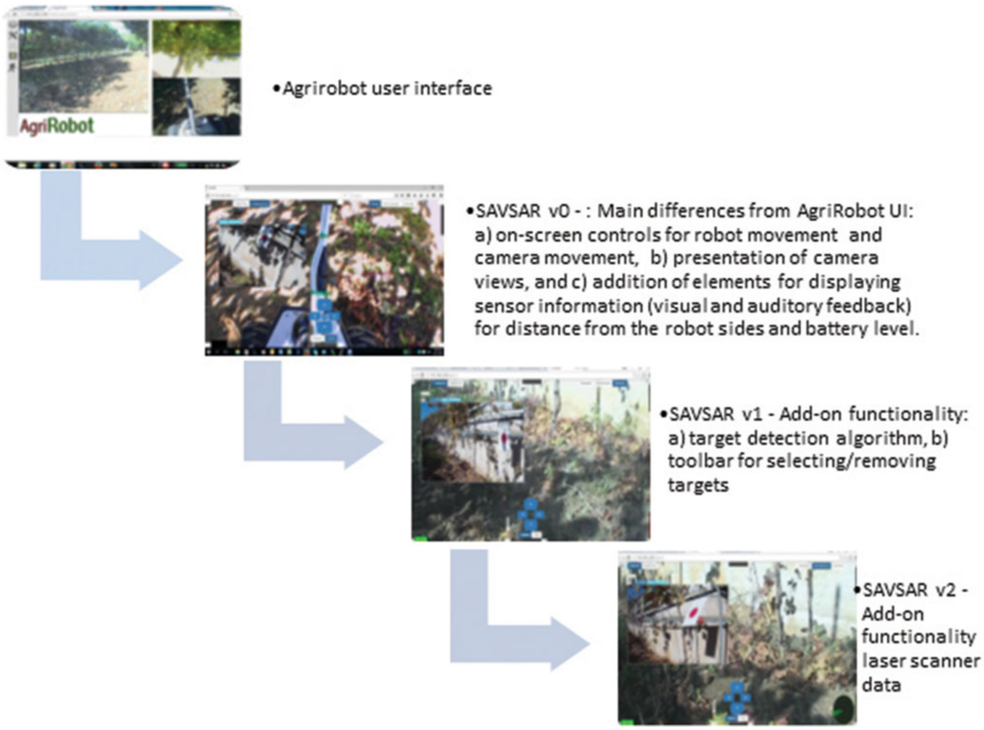


FIGURE 3 User interfaces development stages

3. **Camera control buttons**: These are the buttons with which the operator can select the main central camera view or the peripheral view (camera located at the back-top of the robot). The operator can select which camera to have as the main (full screen) view by using these on-screen buttons or by pressing the keys "p" or "o" on the keyboard. The aforementioned UI components are associated with design guidelines 3 (Visual Design), 4 (Information Presentation), 6 (Interaction Effectiveness and Efficiency), and 7 (Robot Environment/Surroundings Awareness).
4. **Operation mode (autonomous levels) control buttons**: With these buttons the operator can change among the different modes of operation. There are three modes of operation (a) teleoperation, (b) semi-autonomous, (c) autonomous operation. In teleoperation mode, every task is done under the operator control. In semi-autonomous operation mode, the robot operations are done by the robot but with operator approval. In autonomous mode, the robot performs its pre-programmed operations without any operator intervention. If for any reason the operator decides to intervene during the autonomous mode, then the status is changed automatically to semi-autonomous mode. The aforementioned UI component is associated with design guidelines 1 (Platform Architecture and Scalability), 2 (Error Prevention and Recovery), 4 (Information Presentation), 6 (Interaction Effectiveness and Efficiency), and 8 (Cognitive Factors).
5. **Main-frame for camera representation**: It presents in the screen the camera feedback as selected by using the camera buttons. If Central View is selected the feedback from the main central camera (located in the front chassis of the robot) is presented in the main screen. If the Peripheral View is selected then the feedback from the peripheral camera (at the back-top of the robot) is presented in the main frame for camera representation. The aforementioned UI components are associated with design guidelines 3 (Visual Design), 4 (Information Presentation), 6 (Interaction Effectiveness and Efficiency), and 7 (Robot Environment/Surroundings Awareness).
6. **Target view camera frame**: Agricultural operations usually have a "target" such as the crop to harvest or the branch to prune. In our case it is the grapes to spray. The operator can move and resize the target view windows (Picture In Picture: PIP). When the robot is moving, the operator may minimize and move the PIP so as to be able to have a wider view from the central/peripheral cameras. In the target view frame, there are two buttons that are used in either the manual or programmed robot operation. These buttons are used for target detection and to start/stop spraying. If the "target analysis" button is pressed, then the robot initiates the process and presents to the user interface the identified targets by coloring them in red circles (low opacity). When the "start spraying" button is pressed, the spraying process is initiated and the robot sprays the target. The aforementioned UI components are associated with design guidelines 3 (Visual Design), 4 (Information Presentation), 6 (Interaction Effectiveness and Efficiency), and 7 (Robot Environment/Surroundings Awareness).
7. **Navigation and camera buttons**: These buttons are used to move the robot and the robot camera currently activated in the main view (full screen). If the "Navigation" button is selected then the buttons

FIGURE 4 The AgriRobot and SAVSAR user interfaces Top: AgriRobot user interface, Middle: SAVSAR UI Central view, Bottom: SAVSAR UI Peripheral view

are moving the robot (forward, turn left, turn right, backwards). If the "Camera" button is selected then the buttons are moving the currently activated camera; the up-arrow button moves the camera upwards, the down-arrow button moves the camera downwards, and the left and right arrow buttons move the camera left and right, respectively. The central button, labeled as "H" (Home) resets the camera to its pre-set (default) position. The Navigation and Camera control buttons can be also controlled from the keyboard by pressing the "q" and "w" keys, respectively. The aforementioned UI components are associated with design guidelines 1 (Platform Architecture and Scalability), 3 (Visual Design), 4 (Information Presentation), 6 (Interaction Effectiveness and Efficiency), and 7 (Robot Environment/Surroundings Awareness).

For implementation, ROS* was combined with the following web technologies: HTML 5, CSS 3, bootstrap†, Apache Web‡, JavaScript, rosbridge§, php, jQuery¶ and Angular.js#.

3.5.1 | Robot manipulation

Two input devices are used for remote operation of the robot: PC keyboard vs Sony PS3 Gamepad. The Sony PS3 Gamepad is used for the manual movements of the robot over Wi-Fi. The receiver is located inside the robot and connected to one USB port of the robotic platform. The joystick is used for direction and traction and there are various control buttons, such as the speed level buttons that enable selection among five speed ranges: very slow, slow, medium, high, and very high. A keyboard option was added so as to increase the: (a) available input devices for robot control (PS3 gamepad and keyboard), and (b) communication range since the Bluetooth connection of the PS3 was a limiting factor.

Both the PS3 and the keyboard were programmed to send the on/off command from the robot to the sprayer via the Modbus IO. For the keyboard option, the following keys were selected to control the robot: "WASD keys" for movement (in addition to the arrow keys), the "Spacebar" for turning on and off the sprayer and the "Return key" as an emergency stop option. These selections were based on the literature from video games[15] and HRI[16].

4 | EXPERIMENTS FOR HRI EVALUATION

This section presents the four experiments executed in order to evaluate the HRI design of the system during the two R&D projects (AgriRobot and SAVSAR). Table2 summarizes each study setting.

The first experiment aimed to evaluate the usability of three different interaction devices (mouse, Wiimote, digital pen) as input devices for target selection (grape clusters) was conducted in the lab. A second experiment aimed to investigate the effects of different user interface design factors (type of screen output, number of views, and type of robot control input device) and took place in the field. The third experiment conducted in the lab was a heuristic usability evaluation of user interfaces that were developed for a semi-autonomous vineyard robot sprayer. The fourth experiment aimed to evaluate

TABLE 2 Summary of the HRI evaluation experiments reported in this paper

Experiment aim	Experiment type	Sample size	Robotic platform
Usability evaluation of different interaction devices for target selection	Laboratory	50	Simulation
Effects of three interface design factors (type of screen output, number of views, type of robot control input device)	Field	30	Agrirobot (Summit XL)
Heuristic usability evaluation	Laboratory	4	Agrirobot (Summit XL) & SAVSAR (Summit XL HL)
Evaluation of the user experience	Field	5	SAVSAR (Summit XL HL)

* http://www.ros.org

† http://getbootstrap.com

‡ http://httpd.apache.org

§ http://wiki.ros.org/rosbridge

¶ https://jquery.com

\# https://angularjs.org

the user experience of the final user interface was performed in the field.

4.1 | Experiment 1: User testing in the lab investigating effect of target selection input device

The main goal of this study was empirical evaluation of the type of target selection input device (Mouse vs Wiimote vs Digital pen). An interactive prototype of the spraying interface was developed and the usability of different targeting input devices was investigated in the lab. All participants were asked to interact with the prototype in the three following settings: (a) a typical pointing device (mouse) on a desktop computer, (b) a gesture-based interface (Wiimote and projector), and (c) a smart interactive whiteboard using a digital pen (see Fig. 5). Participants experienced the three conditions in random order.

Fifty participants were involved in the experiment, 25 practitioners – farmers and agronomists with average age 41 (SD = 9.9) of which 19 were male and 6 female – and 25 university students majoring in computer science, with average age 22 (SD = 1.5) of which 10 were male and 15 female. Participants were asked to use the three devices to select grape clusters taken from a simulated robot moving along rows in a vineyard. The participants could control the speed of the robot (and the image movement). Five minutes were allowed per input device. The total number of grapes presented was dependent on the robot's speed; with increased speed more grape clusters were visible during the five minutes (because the robot covered a longer distance), for slower speed less grapes were presented. Next, participants completed a perceived usability rating (PUR) questionnaire related to their user experience with the system (ratings from 1 = strongly disagree to 5 = strongly agree) which also included demographic questions. The questionnaire was based on SUS.[55]

Log files documented participants' interaction efficiency (total number of grapes that appeared during the 300 s) and interaction effectiveness (total number of grape clusters actually sprayed). A reliability analysis of the custom-made PUR scale showed a high Cronbach's alpha (cross-conditions average: 0.854; mouse: 0.813, Wiimote: 0.897, digital pen: 0.853), suggesting that the items have relatively high internal consistency. Descriptive statistics for the dependent variables per input device are presented in Table 3.

In terms of effectiveness, a one-way repeated measures ANOVA found a significant main effect of input device on participants' interaction effectiveness; $F(2,98) = 154.01$, $p<0.001$, sphericity was assumed as Mauchly's test was not significant, $\chi^2(2) = 2.50$, $p = 0.287$. Bonferroni post hoc tests showed that both mouse and digital pen were significantly more effective in terms of spraying than Wiimote ($p<0.001$), but no significant difference was found between mouse and digital pen ($p = 0.073$).

A one-way repeated measures ANOVA was conducted to assess whether there were differences among the three input devices in terms of participants' interaction efficiency. Mauchly's test indicated that the assumption of sphericity was not violated; $\chi^2(2) = 1.00$, $p = 0.608$. A significant main effect of input device on participants' interaction efficiency was found; $F(2,98) = 82.72$, $p<0.001$. Bonferroni post hoc tests showed that all differences between the three conditions were significant: digital pen was significantly more efficient than mouse ($p<0.01$) and Wiimote ($p<0.001$), and mouse was significantly more efficient than Wiimote ($p<0.001$).

In terms of perceived usability ratings, a one-way repeated measures ANOVA found a significant main effect of input device on participants' perceived usability rating; $F(1.52,76.46) = 91.79$, $p<0.001$, Greenhouse–Geisser correction was used for the degrees of freedom given that Mauchly's test was significant, $\chi^2(2) = 18.03$, $p<0.001$. Bonferroni post hoc tests showed that participants perceived Wiimote to be significantly less usable compared to both the other two input devices ($p<0.001$), but no significant difference was found between the ratings for mouse and digital pen ($p = 1.000$).

In summary, this experiment found that Wiimote was significantly less effective and efficient, and was perceived as significantly less usable compared to both mouse and digital pen. This finding seems counterintuitive but it might be due to our participants' lack of familiarity with Wiimote and thus needs to be further explored. In addition, digital pen was significantly more efficient compared to the mouse.

4.2 | Experiment 2: User testing in the field investigating effect of screen output, number of views, and robot control input device

The main goal of this study was empirical usability evaluation of the following design factors: (a) type of screen output (PC screen vs Head Mounted Display), (b) number of views (Single View vs Multiple Views), and (c) type of robot control input device (PC Keyboard vs PS3 Gamepad). This field experiment took place at the Experimental Station of the Agricultural Research Institute* at Saittas, Cyprus. The robot was in the vineyard, while the participants controlled the robot remotely from a nearby office in the Station.

Thirty end-users (farmers and agriculturalists) were involved in this field study; 7 females, 23 males, aged 28–65 ($M = 39.8$, $SD = 9.3$). The study was a $2 \times 2 \times 2$ repeated measures experiment; the three design factors were within subject factors and each one of the 30 participants experienced the eight conditions (combinations of the three design factors, e.g., PC screen, single view and PC Keyboard) in random order. Participants were asked to guide the robot along specific vineyard rows avoiding obstacles and spraying clusters. At the end of the experiment, users were asked to complete the SUS[55] questionnaire.

The usability of the different combinations was evaluated by measuring users' interaction effectiveness, interaction efficiency, and overall satisfaction. For the robot navigation task, effectiveness was operationalized by the total number of collisions: fewer collisions, is more effective. For the spraying task, effectiveness was measured by the number of grape clusters sprayed, a binomial random variable with 24 trials (total number of targets). Similarly, efficiency was measured by time on task, which is the overall time required to complete the whole teleoperation task (navigation and spraying). Participants' perceived usability was operationalized by their SUS score. Table 4 summarizes the descriptive statistics of the dependent variables per examined HRI design factor.

* http://www.ari.gov.cy

FIGURE 5 Selecting targets (grape clusters) using a mouse (left), a Wiimote (middle), and a digital pen on a smart interactive whiteboard (right)

TABLE 3 Dependent variables collected per examined target selection input device in the context of Experiment 1. N is the total number of participants involved in the study, M is the mean value of a variable, and SD is the standard deviation of a variable

		Effectiveness: Number of grapes sprayed		Efficiency: Total number of grapes		Perceived usability rating (1-5)	
Factor: Input device	N	M	SD	M	SD	M	SD
Mouse	50	326.66	75.75	356.72	57.07	4.68	0.43
Wiimote	50	157.68	73.15	273.54	47.59	3.23	0.93
Digital pen	50	358.16	63.96	385.86	61.76	4.61	0.51

TABLE 4 Dependent variables collected per examined HRI design factor in the context of Experiment 2. N is the total number of tasks performed by the participants involved in the study, M is the mean value of a variable, and SD is the standard deviation of a variable

			Grapes sprayed (0-24)		Collisions		Completion time (s)		SUS score (0-100)	
Factors	Conditions	N	M	SD	M	SD	M	SD	M	SD
Type of screen output	PC screen	120	9.13	7.65	0.90	1.27	224.17	118.40	65.95	16.16
	Head mounted display	120	9.09	7.77	0.88	1.18	225.41	105.18	62.58	18.81
Number of views	Single view	120	4.19	3.95	1.28	1.44	210.34	89.09	64.14	17.08
	Multiple views	120	14.03	7.39	0.51	0.81	239.24	129.32	64.39	18.14
Robot control inputs	PS3 gamepad	120	8.66	8.12	0.85	1.30	238.27	113.03	57.79	16.44
	PC keyboard	120	9.56	7.25	0.93	1.15	211.30	109.27	70.75	16.30

To examine the effect of the three HRI factors (type of screen output, number of views, and type of robot control input device), on effectiveness (number of grapes sprayed, number of collisions), efficiency (time in inverse scale), and perceived usability (SUS score), the Linear mixed model (LMM), the General Linear Model (GLM), and a logistic regression in the framework of the generalized linear mixed model (GLMM) were used.

In terms of HRI effectiveness, both in spraying and in robot path guidance, the only significant factor was the number of views; $F(1,232) = 294.856$, $p<0.001$ and $F(1,232) = 34.633$, $p<0.001$, respectively. Specifically, participants with multiple views sprayed significantly more grape clusters (M = 14.03 SD = 7.39), compared to those with a single view (M = 4.19, SD = 3.95), with an effect size d = 1.66. In addition, participants with multiple views had significantly less collisions (M = 0.51 SD = 0.81), compared to those with only the single view available (M = 1.28, SD = 1.44), with an effect size d = -0.65.

In terms of HRI efficiency, the number of views and the type of robot control input device were both significant factors; $F(1,29) = 4.732$, $p<0.05$, $\eta^2 = 0.140$ and $F(1,29) = 13.454$, $p<0.001$, $\eta^2 = 0.317$, respectively. Participants interacting with the robot using the PC keyboard and with the multiple views available (M = 222.50, SD = 116.21) required significantly less time to complete the whole task (robot path guidance, identification of targets, and spraying), compared to those in the PS3 gamepad and the multiple views condition (M = 259.10, SD = 109.37).

Finally, in terms of perceived usability, the only significant factor was the type of robot control input device; $F(1,232) = 48.232$, $p<0.001$. The PC Keyboard was at the 70th percentile (M = 70.75, SD = 16.30) which is above average,[54] while the PS3 gamepad controller at the 57th percentile (M = 57.79, SD = 16.44), which is below average, with an effect size d = 0.79.

In summary, the findings of this field study are as follows:

1. Participants were significantly more effective (i.e., had less collisions and sprayed more grape clusters), both in spraying and in robot path guidance, when they had multiple views, than when they had a single view; 60.16% less collisions and 234.84% more grape clusters sprayed with multiple views than with single view.
2. In single view, participants required significantly less time (12.08%) to complete the task, than when they had multiple views.
3. Using the PC keyboard required significantly less time to complete the task by 11.32%, compared to those using the PS3 gamepad.

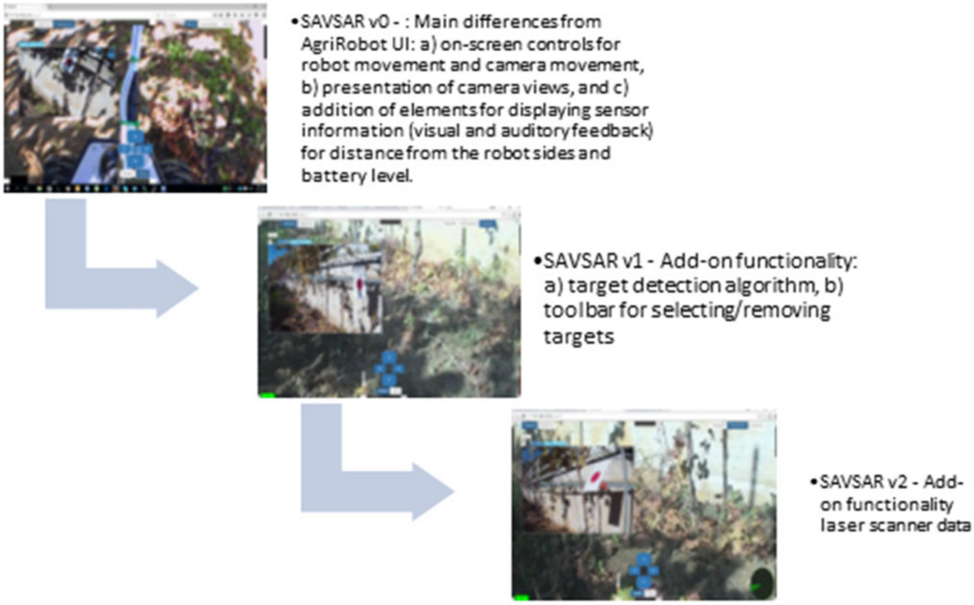


FIGURE 6 Three iterations of the user-centered design process for the SAVSAR user interface

4. The PC keyboard had significantly higher perceived usability (SUS score) by 13 percentiles, compared to the PS3 gamepad controller.

4.3 | Experiment 3: Heuristic usability evaluation of user interfaces for a semi-autonomous vineyard robot sprayer

This study focuses on HRI usability as assessed by expert-based evaluation methods. Heuristic usability evaluations were performed on three versions of a human–robot interface for a semi-autonomous agricultural vineyard robot sprayer. Three iterations of the user-centered design process were followed to ensure the usability of the final product (Fig. 6). Heuristic usability evaluation was conducted for all major versions of the SAVSAR user interface: SAVSARv0, SAVSARv1, and SAVSARv2.

Specifically, SAVSARv0 is the redesigned version of a user interface developed to support (non-semiautonomous) teleoperation of a robot performing agricultural work in the context of the AgriRobot project. In terms of functionality, the main redesigns were: (a) on-screen controls for robot movement and camera movement, (b) presentation of camera views, and (c) addition of elements for displaying sensor information (visual and auditory feedback) for distance from the robot sides and battery level. One important priority when redesigning SAVSARv0 was to enable the operator to use the entire screen and support interaction though either the keyboard or the mouse. SAVSARv1, the next version of the user interface, provides functionality for target pointing; it supports both manual (user points to targets) and automated target specification through a pattern recognition algorithm. SAVSARv2 is a redesigned user interface of the SAVSARv1; it provides additional support in robot movement by displaying a radar control with distances from obstacles around the robot.

Four usability experts—an adequate number to ensure reliable results[53]—experimented with the system and conducted heuristic usability evaluations of all three SAVSAR user interfaces. The evaluators were situated at the Hellenic Open University Software Quality Assessment laboratory* at Patras, Greece and remotely controlled (over HTTP) the robot, which was located in Cyprus at the Open University of Cyprus† premises. An appropriate lab-simulation environment was created, including various paths and targets (Fig. 7). Specifically there were in total eight targets (green and red circles). The participating evaluators were asked to spray the green circles and avoid spraying the red circles. After each individual evaluation, the participating evaluators conducted a focus group to group and prioritize the identified usability issues using established severity rating schemes.[64] In specific, they rated each usability issue on a scale from 1 (a little important, it does not significantly affect the user interaction) to 5 (extremely important, catastrophic problem that may result in unsuccessful task).

The following set of research-based heuristics for the design of robot teleoperation, which have been developed in our previous work[14] were used:

1. Platform architecture and scalability: Provide the flexibility to iterate robotic and computing technological developments in the UI of the HRI system.
2. Error prevention and recovery: Provide information and alerts to avoid and recover from user errors.
3. Visual design: Provide an aesthetic, clear, and simple design of the UI with the relevant information necessary.
4. Information presentation: Provide the necessary information, in the right context, moment, and modality.

* http://quality.eap.gr

† http://www.ouc.ac.cy

FIGURE 7 The lab setting and paths with spraying targets. Participating evaluators were asked to spray the green circles

TABLE 5 Summary of the SAVSARv2 heuristic evaluation results. Total problems found by four experts

Heuristic Number	Usability Problem	Problem Severity 1	2	3	4	5	Average Problem Severity
1	0						
2	0						
3	1	1					1.0
4	1		1				2.0
5	1	1					1.0
6	4	1	1		1	1	3.0
7	2		1	1			2.5
8	0						
Total	9	3	3	1	1	1	1.9
Percentage	100%	33%	33%	11%	11%	11%	

5. Robot state awareness: The knowledge that the robot has about its own systems' situation and the information it gives to the operator about its health status and mode of operation.
6. Interaction effectiveness and efficiency: Provide efficient and effective interactions between human and robot.
7. Robot environment/surroundings awareness: Provide spatial information about the robot's surroundings and the environment where it is operating.
8. Cognitive factors: Use mental models and metaphors to lower the cognitive load.

The main problems identified and resolved in SAVSARv0 and v1 are presented in the appendix. Table 5 shows the overall usability problems identified for SAVSARv2 (the final user interface), by summing the problems found by each evaluator.

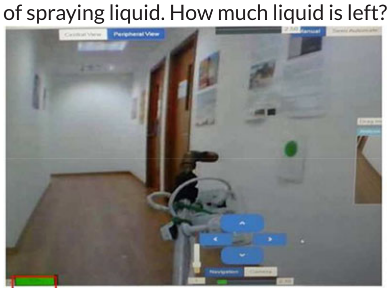
Representative examples of the identified usability issues are the following:

1. Add associated camera icons on a schematic of the robot so that the user knows the exact placement of the available cameras.
2. Provide a way to inform the user about the available shortcuts (e.g., under the button label, tooltip, help page with shortcuts etc.).
3. Resolve bug so that functionality of adding multiple targets is available.
4. In the radar, provide appropriate information about the obstacles' distance (e.g., radius of each circle in meters).

In the following, we show one example from the evaluation report of the SAVSARv2 user interface, about usability violations and the solution suggested by the participating experts.

SAVSARv2

Identified problem: Missing information relating to the level of spraying liquid. How much liquid is left?



Heuristic violated: 4. Information presentation

Problem severity: 2/5

Solution Proposal: Show an appropriate indication (e.g., gauge icon and level of liquid left).

The heuristic evaluation studies indicated that the expected number of usability issues was 42 for SAVSARv0, 15 for SAVSARv1 and

4 for SAVSARv2, respectively. The total number of expected problems for the each system was calculated using the following formula[65]:

$$N = \frac{1-(1-j)^{i}}{Problemsfound(i)}$$

where N is the total number of expected usability problems, i is the number of independent experts-evaluators, ProblemsFound(i) is the total number of unique usability issues identified by the participating evaluators, and j is the average proportion of problems found by a single evaluator. According to [10], the average number of usability problems observed in a rather mature interactive system is 35. In addition, the average severity of the identified usability issues was characterized as medium for SAVSARv0, low for SAVSARv1, and very low for SAVSARv2 respectively.

These findings provide evidence (in terms of usability issues identified by experts), that the final version of the system provides satisfactory services to its typical users. However, we also field-tested the final version of the user interface (SAVSARv2); this experiment is delineated in the following section.

4.4 | Experiment 4: Field user experience testing of the final SAVSAR user interface

The main goal of this experiment was to evaluate the user experience of the final version of the user interface (SAVSARv2). This field experiment took place at the Experimental Station of the Agricultural Research Institute at Saittas, Cyprus and involved end-users (farmers).

Five participants took part in the experiment; 3 male and 2 female with an average age of 38.8. This number of participants is adequate to uncover the most important usability issues[48], particularly in systems with specialized users or users that are hard to find/reach in specific times, as in our case. Participants were asked to follow a user scenario in order to move the robot along a path and spray identified targets. During participants' interaction with the system the following measures were documented: (a) time on task, (b) number of targets sprayed, and (c) number of collisions. After the experiment, participants were asked to complete three questionnaires: (a) a questionnaire to collect demographic data, (b) the System Usability Scale (SUS), and (c) the User Experience Questionnaire (UEQ). Both SUS[55] and UEQ[66] are standardized questionnaires that provide reliable and valid results in terms of the constructs they measure.

In terms of interaction effectiveness, all participants had a task success rate of 100% in both spraying the identified targets, and managing to avoid collisions (0 collisions with obstacles for all participants). Interaction efficiency was measured as the time required (in seconds) to complete the whole task, that is to navigate in the robot pathway, approximately 50 meters, and to spray the four targets. The average time for this was 330 seconds (5.5 minutes).

In terms of perceived usability, the average SUS score for the system was 74.5. According to a dataset of over 3500 surveys and 273 studies,[54] the evaluated system is characterized as "good to excellent." Regarding overall user experience the system was evaluated positively (>0.8) on the UEQ scales. Comparisons with existing benchmark data for UEQ[66] showed that SAVSARv2 was perceived as "excellent" in terms of attractiveness, perspicuity, efficiency, dependability, and stimulation, and "good" in terms of novelty. All in all, SAVSARv2 was rated among the 10% best results in all but the novelty subscale (Fig. 8).

5 | DISCUSSION: GENERALIZATION

Both field and laboratory experiments investigated HRI design aspects of agricultural spraying robots. Field experimental results confirm findings from Yanco and Drury[40] who concluded that, "*when teleoperating a robot, operators rely on the video to determine the best way to navigate the environment.*" The placement of a camera on the top-back of the robot enhanced the surroundings awareness, while the placement of a camera on the end-effector sprayer improved target identification, thus improving activity awareness corresponding to work presented by Murakami et al.[25] This corresponds also with conclusions of previous research "*a video centric interface is more effective in providing good surroundings and activities awareness*" (Drury et al.[67])

The system effectiveness (58% highest spray success) was in similar range to low performance of harvesting robots average 66%.[3] However, it must be noted that in the current experiments detection was conducted solely by the human operator without automatic detection algorithms. Furthermore, there was an added complexity of detecting the clusters while advancing along the row. Autonomous detection rates average about 85%, in general.[68] Previous research has proven that detection rate can be improved by incorporating more advanced detection algorithms and combining human in the loop.[23] Blackmore et al.[69] argue that the 95% is the lowest barrier for the detection rate in order for the spraying process to be economically feasible. Correa et al.[70] reported a 95% hit rate for red grape clusters but with artificial white background. Future work should incorporate into the developed system automatic algorithms and human–robot collaboration to improve detection performance.

Future work is also needed to improve algorithms both for robot navigation and target identification. In terms of the user interface, based on the lab and field testing of SAARv2, the next version of the system could benefit from: (a) an embedded representation of the robot's body in the user interface displaying sensors' information and robot's direction in relation to the active camera views, (b) embedded help explaining some functionality and controls, e.g., first time user tutorial, (c) additional information that is important for the task, e.g., remaining level of spraying liquid, and (d) improvements in the visual design of the user interface, e.g., larger text labels to increase readability from portable devices.

Designing usable human–robot interaction supports operators to perform complex tasks.[28,30] Safety and effectiveness are paramount in applying robots in field applications, such as agriculture, search and rescue, mining, military robotics et cetera. Even when autonomous robots are going to be a standard or routine, the role of the human and of a user interface will be always there. This is not merely a need for safety and supervising/monitoring a machine. It's more about

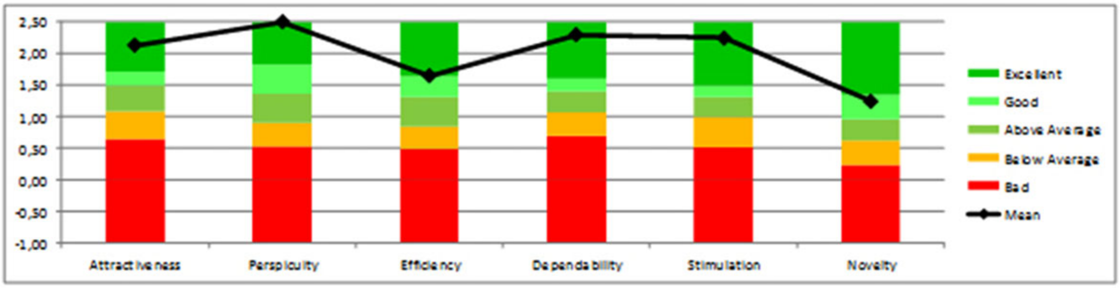


FIGURE 8 Comparison of our study UEQ data with benchmark UEQ data[66]

communication needs, building a trust for cooperation and collaboration spirit between human and robots.

The work described in this paper summarizes an approach to understand the need for human–robot collaboration/interaction specifically for mobile agricultural field robots. This approach includes aspects of how a robotic system should be designed (i.e., asking users how they expect the robot to perform tasks), using heuristics and design guidelines (gathered from a large body of literature specific for mobile field robots) to develop the user interface, and iteratively testing the user experience both in the lab and in the field in order to improve system design.

6 | CONCLUSION

This paper has addressed developments of semi-autonomous agricultural robots and human–robot collaborative spraying through a human–robot interface. Although it investigates a vineyard sprayer platform, the method can be adapted to many other mobile robot field applications.

A methodology to transform a generic mobile robotic platform to an agricultural robot sprayer, addressing both hardware and user interface design aspects, has been presented. The methodology was applied in the context of two research projects and the result was field-tested. Field studies provided evidence for the increased usability of the SAVSARv2 (final) system, which may result in high adoption from its end users.

Limitations of the current system include the small size of robot platform and of the sprayer tank, which is a limiting factor for large vineyards. An alternative solution would be to add the intelligence and robotic technology on a regular tractor, such as the ones currently used by farmers, and remove the farmer from the tractor (i.e., engineering of a driverless tractor sprayer).

Additional experiments are underway to evaluate different methods to remotely control the robotic arm and test additional versions of the user interface. It would be interesting to apply a framework of the levels of autonomy[71,72] in human–robot collaboration research, including switching between collaboration levels.[73] The framework determines (a) whether the current robot operation is pre-programmed ("robot-controlled") or directed on-line ("human-operator") and (b) the current mode of operation (autonomous, semi-autonomous or teleoperated) and collaboration level.

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APPENDIX

1. **Heuristic evaluation of SAVSARv0**

The main problems identified and resolved in SAVSARv0 are the following.

Heuristic Number	Usability Problem	Problem Severity 1	2	3	4	5	Average Problem Severity
1	0						
2	2				1	1	4.5
3	3			1		2	4.3
4	7	2	1	1	3		2.7
5	7			2	1	4	4.3
6	3	3			1	1	1.0
7	2		1	1			2.5
8	5				4	1	4.2
Total	29	5	2	5	9	8	3.4
Percentage	100%	17%	7%	17%	31%	28%	

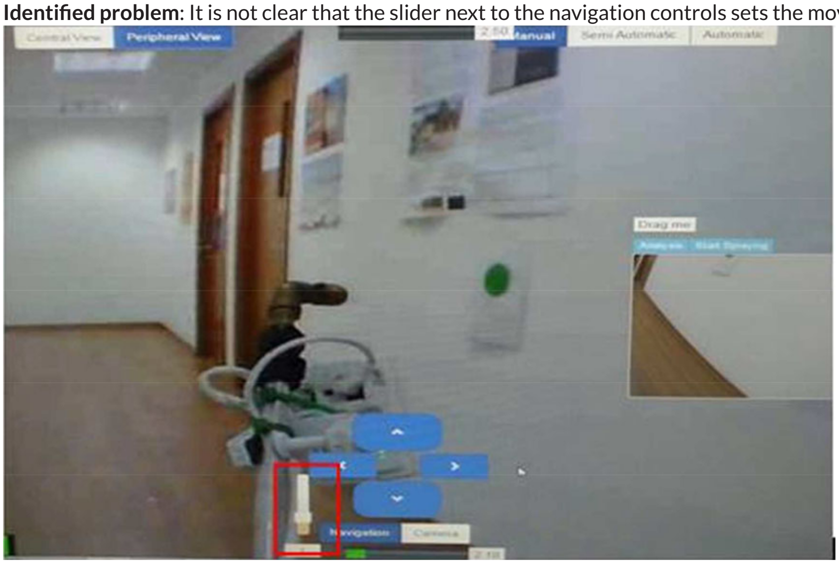
Representative examples of the identified usability issues are the following:

1. User should be able to somehow know what "area" will be analyzed by the target identification algorithm (e.g., overlaid grid showing "range").
2. In automated modes, display the remaining time for auto-spraying. The user should also be able to hide this information (if he wants to).
3. End-effector view should return in a different state if all targets have been successfully sprayed, e.g., either icons of sprayed targets or no targets at all.
4. All numbers should be displayed in metric units (i.e., meters).
5. The minimum and maximum speed of the associated speed control should be added.

In the following, we show one example from the evaluation report of the SAVSARv0 user interface, about usability violations and the solution suggested by the participating experts.

SAVSARv0

Identified problem: It is not clear that the slider next to the navigation controls sets the movement speed of the robot.



Heuristic violated: 4 Information presentation

Problem severity: 2/5

Solution Proposal: Add a label for the control (e.g., speed).

2. Heuristic evaluation of SAVSARv1

The main problems identified and resolved in SAVSARv1 are the following.

		Problem Severity					
Heuristic Number	**Usability Problem**	**1**	**2**	**3**	**4**	**5**	**Average Problem Severity**
1	0						
2	2			1	1		3.5
3	0						
4	4	3	1				1.3
5	5		2	3			2.6
6	5			2	3		3.6
7	0						
8	6	1	4		1		2.2
Total	22	4	7	6	5	0	2.6
Percentage	100%	18%	32%	27%	23%	0%	

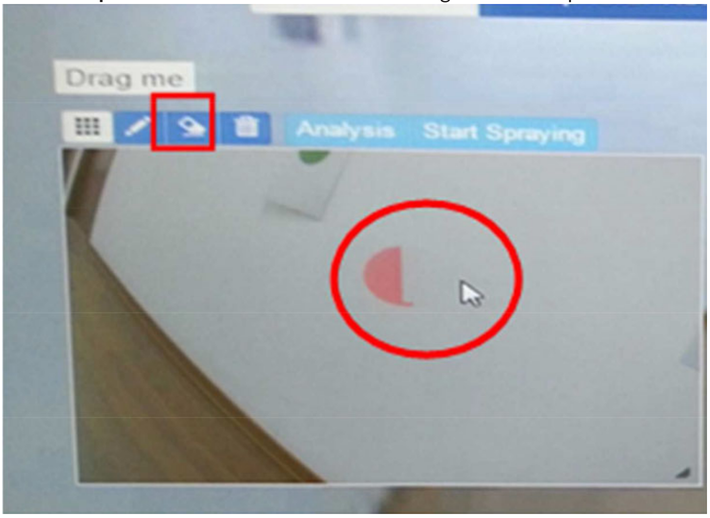
Representative examples of the identified usability issues are the following:

1. Add a confirmation message when the erase-all-targets tool is used. For more experienced users, there might be an option (stored in user preferences) for not showing this message (and maybe others in the future too).
2. Clarify the currently active control (e.g., speed slider, button for moving camera/robot, etc.)
3. The button "Analysis" in the algorithm settings should either close the dialogue or bring forward the end-effector view with the identified targets.
4. Adding or removing circle-targets should appropriately change the pointing cursor (e.g., a circle with a cross in the middle for adding targets, a rubber with a radius for removing targets).
5. Show an appropriate icon (e.g., battery icon) or/and label (e.g., battery) for the battery indicator because it could be also something else (e.g., level of spraying liquid). In addition, it might be more useful to show an estimation of the remaining time instead of % battery level.
6. Add appropriate icon labels or tooltips on the buttons related to target specification.
7. In the algorithm settings, use appropriate language easily interpreted from the end users.

In the following, we show one example from the evaluation report of the SAVSARv1 user interface, about usability violations and the solution suggested by the participating experts.

SAVSARv1

Identified problem: Tool that deletes circles-targets should a-priori show the area to be marked.



Heuristic violated: 6 Interaction effectiveness and efficiency

Problem severity: 4/5

Solution Proposal: When the user wants to delete circle-targets the pointing cursor must be replaced with an appropriate symbol (e.g., a rubber with a radius).