School of Pure and Applied Sciences

# User Interfaces for Human-Robot Interaction:

# Application on a Semi-Autonomous Agricultural Robot Sprayer

A dissertation submitted in partial fulfillment of the

requirements for the doctoral degree

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June, 2016

**ISBN 978-9963-695-49-2**

## *VALIDITY PAGE*

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**Title of Doctoral Dissertation:** User Interfaces for Human-Robot Interaction: Application on a Semi-Autonomous Agricultural Robot Sprayer

**The present doctoral dissertation was written in the context of the Doctoral Programme in Information and Communication Systems at the School of Pure and Applied Sciences of the Open University of Cyprus and was successfully defended by the candidate on the 23rd of June 2016.**

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**Abstract**

This dissertation focuses on the usability of user interfaces for tele-operated and tele-manipulated mobile robots, with an application on a semi-autonomous agricultural robot sprayer.

Semi-autonomous operation of agricultural robots is proposed including a framework for its levels of autonomy. In this case, the robot, in addition to whatever pre-programmed operation can do, is in communication with a human operator (farmer), who intervenes when needed. 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".

The objective of this dissertation is to study the design and evaluation aspects of a user interface that supports human-robot interaction, for semi-autonomous agricultural spraying robots. Various aspects related to the user interface design and evaluation that can enhance human-robot interaction are investigated within this thesis including: 1) custom transformation of a robotic platform into a piece of agricultural machinery, 2) proposing a framework for semi-autonomous robot modes of operation, 3) a taxonomy of user interface guidelines / heuristics for tele-operated field robots, 4) studies and experiments with the design aspects of user interfaces for robot tele-operation and tele-manipulation for the specific tasks of navigation, target identification and spraying, and 5) development and evaluation of suitable interfaces with enhanced human-robot interaction awareness to the farmer to effectively tele-operate a semi-autonomous vineyard robotic sprayer.

Specifically, this dissertation starts with the methodological approach followed to transform an existing robotic platform to a semi-autonomous agricultural robot sprayer (AgriRobot). This is followed by the proposed levels of autonomy. The semi-autonomous mode is the mode of operation where one or more operations are in manual mode and one or more operations are in autonomous mode. The robot has operations both in manual and in autonomous modes, concurrently. This formal framework brings out human-robot interaction theoretical issues of human-robot interaction and more practical issues specific to the user interface design framework.

This is followed by a systematic approach to develop a taxonomy of design guidelines for robot teleoperation developed from a focused literature review of robot teleoperation. A list of user interface design guidelines was assembled, open card sorting and a focus group were used

to classify them, and closed card sorting was employed to validate and further refine the proposed taxonomy. The initially obtained set of 70 guidelines is grouped into eight categories: platform architecture and scalability, error prevention and recovery, visual design, information presentation, robot state awareness, interaction effectiveness and efficiency, robot environment/surroundings awareness, and cognitive factors. The semi-autonomous agricultural robot sprayer constructed was used as an application case study for implementation and field evaluation. The proposed guidelines taxonomy was used heuristically to evaluate the usability of existing user interfaces of the teleoperated agricultural robot sprayer.

In terms of experimentation, the first step was to determine how to begin work in this research area. Initially, without the resources to experiment in the field, as a first step we used an effective test-bed - a simulation experiment in a lab – to evaluate the usability of three different input devices. The goal was to evaluate the selection input device (Mouse vs Wiimote vs Digital pen) for marking the targets (grape clusters). Results indicated usability preference for the mouse and the digital pen. Later, in a field experiment, the usability of different interaction modes for agricultural robot teleoperation was also investigated. Specifically, two different types of peripheral vision support mechanism, two different types of control input devices, two different types of output devices and the overall influence of the user interface on observed and perceived usability of a teleoperated agricultural sprayer were examined. Specific recommendations for mobile field robot teleoperation to improve HRI awareness for the agricultural spraying task were drawn. A value-added from this dissertation is the placing of a camera on top of the end-effector sprayer to provide accurate target identification and spraying verification, thus improving activity awareness. Similarly, placing a camera at the back-top of the robot provides peripheral vision and enables the operator to locate obstacles around the robot wheels, thus improving location and surroundings awareness. Regarding the input/output devices, the PC keyboard and monitor were preferred over the PS3 gamepad and the head mounted display.

The dissertation concludes with a discussion on the research findings and suggestions for future research directions. In sum, this work described aspects of how a robotic system should be designed (i.e. asking users how they expect the robot to perform tasks), defining levels of autonomy (including levels and type of communication), using heuristics and design guidelines (gathered from a large body of literature specific for mobile field robots) to develop and evaluate the user interface. In terms of future research directions, these include the robotization of a tractor. In this case, the tractor can be used for several agricultural tasks which could enhance its financial feasibility. In the case of a new robot with a robotic arm installed and additional sensor capabilities (e.g. laser and LIDAR scanners), a new user interface should be developed, following the taxonomy guidelines, and experiment with other teleoperation equipment. In terms of user interface technologies, with the emergence of new sensor technologies and 3D cameras improvements, it would be worthwhile to develop user interfaces with augmented reality capabilities to investigate their effect on situational awareness of operators when using tele-robotics. Finally, it would be interesting to apply the proposed framework of the levels of autonomy to other related work in human-robot collaboration research (i.e. search and rescue robotics) including switching between collaboration levels.

**Περίληψη**

Η παρούσα διδακτορική διατριβή μελετά την ευχρηστία διεπαφών χειρισμού ρομπότ και ειδικότερα τον τηλεχειρισμό ημιαυτόνομου ρομποτικού ψεκαστήρα αμπελώνων.

Σχεδιάστηκε, αναπτύχθηκε, δοκιμάστηκε και αξιολογήθηκε ημιαυτόνομο γεωργικό ρομπότ, από όπου προέκυψε και το πλαίσιο λειτουργίας του. Ένα ημιαυτόνομο ρομπότ, επιπρόσθετα των προγραμματισμένων εντολών που εκτελεί, είναι σε επικοινωνία με τον χειριστή (εν προκειμένου του. αγρότη), ο οποίος παρεμβαίνει όταν θελήσει ή χρειαστεί. Ο αγρότης (χειριστής του ρομπότ) δεν είναι αναγκαίο να βρίσκεται και αυτός στο χωράφι. Για λόγους ασφάλειας και εργασιακής άνεσης, (όπως κατά τη διάρκεια του ψεκασμού όπου και η περίπτωση που εξετάζει η διατριβή), αλλά και για λόγους αποδοτικότητας (π.χ. ταυτόχρονος τηλεχειρισμός πολλών ρομπότ, κάτι που δεν εξετάζει αυτή η διατριβή), θεωρείται ότι ο αγρότης δε βρίσκεται στο χωράφι μαζί με το ρομπότ.

Στόχος της διατριβής είναι να μελετήσει τις διάφορες πτυχές που αφορούν στον σχεδιασμό και στην αξιολόγηση των διεπαφών χρήστη που να υποστηρίζουν την επικοινωνία ανθρώπου με ρομπότ, και ειδικότερα ημιαυτόνομων γεωργικών ρομπότ ψεκασμού αμπελώνων. Οι διάφορες πτυχές που σχετίζονται με την ενίσχυση/ βελτίωση της επικοινωνίας ανθρώπου με ρομπότ τις οποίες περιλαμβάνει η διατριβή αφορούν: 1) την προσαρμοσμένη μετατροπή μιας ρομποτικής πλατφόρμας σε ένα γεωργικό ρομποτικό ψεκαστήρα, 2) την εισήγηση/ πρόταση ενός πλαισίου για ημιαυτόνομα ρομπότ και τους τρόπους λειτουργίας τους, 3) την ταξινόμηση οδηγιών για σχεδίαση διεπαφών χρήστη για τηλεχειριζόμενα ρομπότ πεδίου, 4) τη μελέτη και πειραματισμό των πτυχών σχεδίασης διεπαφών χρήστη για τηλεχειριζόμενα ρομπότ και ειδικότερα για την κίνηση στο πεδίο, τον εντοπισμό στόχων και της διαδικασίας ψεκασμού, και 5) την ανάπτυξη και αξιολόγηση κατάλληλων διεπαφών χρήστη που να ενισχύουν/ βελτιώνουν την επίγνωση που έχει ο γεωργός κατά την επικοινωνία με ένα ημιαυτόνομο ρομπότ ψεκαστήρα.

Πιο συγκεκριμένα, η παρούσα διατριβή κάνει αρχή με τη μεθοδολογική προσέγγιση που ακολουθήθηκε για τη μετατροπή μιας ρομποτικής πλατφόρμας σε ένα ημιαυτόνομο γεωργικό ρομπότ ψεκαστήρα (AgriRobot). Ακολούθως, προτείνει ένα πλαίσιο με τα διάφορα επίπεδα αυτονόμησης του ρομπότ. Ημιαυτόνομη είναι η λειτουργία όταν τουλάχιστον μία λειτουργία του ρομπότ είναι αυτόνομη/ ες και ταυτόχρονα, μία άλλη

ή περισσότερες λειτουργίες γίνονται από τον χειριστή. Αυτό το πλαίσιο λειτουργίας φέρνει στην επιφάνεια τόσο θεωρητικά ζητήματα που αφορούν την επικοινωνία ανθρώπου με ρομπότ, όσο και πρακτικά ζητήματα που αφορούν τους σχεδιαστές διεπαφών χρήστη.

Ακολούθησε η διαδικασία ταξινόμησης οδηγιών σχεδιασμού διεπαφών χρήστη, η οποία στηρίχτηκε σε ολοκληρωμένη βιβλιογραφική ανασκόπηση για τηλεχειριζόμενα ρομπότ. Αρχικά, καταρτίστηκε ένας κατάλογος οδηγιών σχεδίασης διεπαφών χρήστη. Ακολούθως, αυτές κατηγοριοποιήθηκαν με τη χρήση της μεθόδου ανοιχτής διαλογής καρτών και ομάδας εστίασης. Τέλος, με τη μέθοδο της κλειστής διαλογής καρτών η ταξινόμηση επικυρώθηκε. Οι αρχικές οδηγίες που είχαν εντοπιστεί (70 συνολικά), ομαδοποιήθηκαν σε οκτώ κατηγορίες: αρχιτεκτονική πλατφόρμας και επεκτασιμότητα, πρόληψη σφαλμάτων και αποκατάσταση, οπτικός σχεδιασμός, παρουσίαση πληροφοριών, επίγνωση κατάστασης του ρομπότ, αποδοτικότητα και αποτελεσματικότητα της αλληλεπίδρασης, επίγνωση του περιβάλλοντος-χώρου, και γνωστικοί παράγοντες. Το ημιαυτόνομο γεωργικό ρομπότ-ψεκαστήρας χρησιμοποιήθηκε ως μελέτη περίπτωσης εφαρμογής διεπαφών χρήστη, οι οποίες εφαρμόστηκαν και αξιολογήθηκαν στο πεδίο (πειράματα στο χωράφι).

Εξετάστηκε η ευχρηστία διαφόρων τρόπων αλληλεπίδρασης τηλεχειρισμού γεωργικών ρομπότ. Αρχικά, μέσω της μεθόδου προσομοίωσης, αξιολογήθηκαν τρεις διαφορετικές συσκευές εισόδου. Ο στόχος ήταν η αξιολόγηση της ευχρηστίας των συσκευών Ποντίκι vs Wiimote vs Ψηφιακό Στυλό κατά την επιλογή στόχων (τσαμπιών σταφυλιών). Τα αποτελέσματα έδειξαν την προτίμηση των συμμετεχόντων για το Ποντίκι και το Ψηφιακό Στυλό. Ακολούθησαν πειράματα στο πεδίο. Συγκεκριμένα, εξετάστηκαν δύο διαφορετικοί τύποι μηχανισμών για υποστήριξη της περιφερειακής όρασης, δύο διαφορετικοί τύποι συσκευών ελέγχου και δύο διαφορετικοί τύποι συσκευών εξόδου για οπτική απεικόνιση. Επιπλέον, εξετάστηκε η συνολική επίδραση των διεπαφών χρήστη για τηλεχειριζόμενα ρομπότ στην παρατηρούμενη και αντιλαμβανόμενη ευχρηστία. Έχουν προκύψει συγκεκριμένες συστάσεις που βελτιώνουν την επίγνωση αλληλεπίδρασης ανθρώπου-ρομπότ για την εργασία του γεωργικού ψεκασμού. Για παράδειγμα, η τοποθέτηση κάμερας πάνω από τον τελεστή ψεκασμού βοηθά στον εντοπισμό των στόχων και στην επιβεβαίωση ότι έχουν ψεκαστεί, άρα βελτιώνει την επίγνωση της ενέργειας που εκτελεί το ρομπότ. Παρομοίως, η τοποθέτηση κάμερας στο πάνω-πίσω μέρος του ρομπότ επιτρέπει την περιφερειακή όραση, κάτι που βοηθά τον χειριστή να εντοπίζει πιθανά εμπόδια γύρω από το μονοπάτι που ακολουθεί το ρομπότ, και άρα βελτιώνει την επίγνωση του περιβάλλοντος χώρου που βρίσκεται και ενεργεί το ρομπότ. Αναφορικά με τις συσκευές ελέγχου και συσκευές εξόδου, βρέθηκε ότι προτιμάται το πληκτρολόγιο και η οθόνη του υπολογιστή έναντι των PS3 gamepad και των ψηφιακών γυαλιών.

Η διατριβή καταλήγει με συγκεκριμένα συμπεράσματα, σχολιασμό και γενίκευση των ερευνητικών αποτελεσμάτων, ενώ προτείνει μελλοντικές ερευνητικές κατευθύνσεις. Εν συντομία, η διατριβή περιγράφει πτυχές για το πώς ένα γεωργικό ρομποτικό σύστημα θα πρέπει να σχεδιαστεί, καθορίζει τα επίπεδα αυτονομίας, και χρησιμοποιεί την ευρετική μέθοδο και κατευθυντήριες γραμμές σχεδιασμού για ανάπτυξη διεπαφών χρήστη. Όσον αφορά τις μελλοντικές ερευνητικές κατευθύνσεις, αυτές περιλαμβάνουν την ρομποτοποίηση τρακτέρ. Σε τέτοια περίπτωση, το τρακτέρ-ρομπότ μπορεί να χρησιμοποιηθεί για διάφορες γεωργικές εργασίες. Στην περίπτωση ενός νέου ρομπότ με ένα ρομποτικό βραχίονα όπου θα υπάρχουν πρόσθετες δυνατότητες αισθητήρων (π.χ. λέιζερ και LIDAR), θα πρέπει να αναπτυχθεί ένα νέο περιβάλλον εργασίας χρήστη, ακολουθώντας τις κατευθυντήριες γραμμές ταξινόμησης που προτείνει η διατριβή. Από την άποψη των τεχνολογιών διεπαφών χρήστη, με την εμφάνιση των νέων τεχνολογιών αισθητήρων και 3D κάμερες θα άξιζε τον κόπο να αναπτυχθούν διεπαφές χρήστη με δυνατότητες επαυξημένης πραγματικότητας για να διερευνηθούν οι επιπτώσεις τους στην επίγνωση της κατάστασης επικοινωνίας ανθρώπου-ρομπότ. Τέλος, θα ήταν ενδιαφέρον να εφαρμοστεί το προτεινόμενο πλαίσιο των επιπέδων της αυτονομίας και σε άλλες συναφείς εργασίες όπως για παράδειγμα σε ρομπότ εντοπισμού και διάσωσης, συμπεριλαμβανομένων και των επιπέδων συνεργασίας/επικοινωνίας.

**In loving memory of my mother**

# ACKNOWLDEGMENTS

I wish to give thanks to all those who in one way or another have provided guidance, helped and supported me during these past seven years that made this work possible.

First of all, I would like to thank my supervisor Professor Thanasis Hadzilacos, for his support, encouragement and belief in me from the very beginning of this work. His guidance and the many hours of discussion and exchange of ideas have provided profound inspiration. I really enjoyed our talks through which you helped and taught me to seek for answers, always question about everything, and think about solutions and to trust and believe myself.

Equally, a huge thank you to my co-supervisor Professor Yael Edan, for her continuous interest in my work, her advices, support and encouragement. Her experience in the field of robotics and her motivation to work in this exciting area of human-robot cooperation, gave insight to my work. Your guidance has helped me improve my knowledge in this area and your comments in the draft manuscripts helped in improving my writing skills.

Alike, special thanks to my third advisor Assistant Professor George Christou, whose work in human-computer interaction has been an inspiration from the very beginning. I thank him for his continuous will to help throughout my studies. I also wish to thank him for his support during the design and execution of experiments.

I feel privileged and honored (and lucky) to be one of your students, and for having this great opportunity to work with you; for that I am forever grateful.

I would like to thank Professor Michalis Xenos and Dr. Christos Katsanos, and their research team from Software Quality Research Group of the Hellenic Open University, whose collaboration with was significant for the implementation of the two research funded projects AgriRobot and SAVSAR. I would like to particularly thank Christos for the many hours he put in reading and commenting the many preliminary drafts of manuscripts that were submitted in journal and conference proceedings. His help was valuable in improving my writing to be precise and accurate. His help was also instrumental in clarifying the goals and arguments, as well as defining and analyzing the experiments carried out in this work.

Special thanks to Professor Yisrael Parmet, from the Ben-Gurion University of the Negev, for his help in the statistical analysis of the field experiments. My thanks also to

Ron Berenstein and Panagiotis Kyriakou with whom I worked at the beginning of my studies and they helped in selecting an appropriate robotic platform for this work.

I would like to acknowledge the contribution of Ioannis Constantinou (Istognosis) in the design and implementation of the user interfaces. I would also like to thank George Vassiliades (Agrowise) who helped in the design and installation of the electrical sprayer on our robotic platform. My thanks also to Roberto Guzman and Santiago Fuster from Robotnik Automation S.S.L., with whom I have collaborated extensively while working with our Summit XL robot.

I wish to thank all volunteers for participating in the experiments. My sincere thanks to students from: the University of Cyprus (Dr. Christos Fidas), the European University of Cyprus (Dr. G. Christou) and the Hellenic Open University (Dr. M. Xenos and Dr. C. Katsanos), for the cooperation during the laboratory experiments. I would also like to thank the staff of the research stations of the Agricultural Research Institute at Saittas, Zygi and Acheleia for their help and cooperation during the field experiments.

This work was partially funded by Research Promotion Foundation of Cyprus and the Greek General Secretariat for Research and Technology under the research projects AGRIROBOT and SAVSAR, respectively. This work was also supported by the Helmsley Charitable Trust through the Agricultural, Biological and Cognitive Robotics Institute and by the Rabbi W. Gunther Plaut Chair in Manufacturing Engineering, both at Ben-Gurion University of the Negev, Israel. I gratefully acknowledge their support.

Finally, special thanks to all my dear friends and to my extended family for their encouragement and interest in the progress of my work.

The greatest gratitude is owed to my wife Maria and to my three children Constantina, Raphael and Michaella, for their love and support, as well as for their understanding (for not being always there), during the preparation and completion of this work.

Without all of you, I would not be who I am today.

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# Chapter 1. Introduction

**Dissertation overview**

This dissertation touches upon four disciplines: Agriculture, Robotics, Human-Computer Interaction, and Human-Robot Interaction. Agriculture is the application area where the real-world challenges arise for food safety and food security [72, 185]. Robotics is the basis of the solution proposed, which in turn presents research issues in Human-Robot Interaction. Any kind of human-machine interaction requires some interface. This dissertation examines research topics related to human-computer interaction (HCI) and human-robot interaction (HRI); specifically, the design aspects and usability evaluation of user interfaces suitable for agricultural robot teleoperation. An application for vineyard spraying is presented with a semi-autonomous agricultural robot sprayer. This chapter presents the problem statement, the research objectives and research significance, and the contributions and innovations of this work.

## 1.1. Description of the problem

Working in an agricultural field is certainly not an easy task. To complete the many operations required to produce crops such as plowing, planting, weeding, pruning, spraying, and harvesting, require many helping hands. In addition, these are labor intensive tasks and workers need to work long hours, often under harsh weather conditions, and typically a low pay is associated with this kind of work. As a result, agriculture (and rural life in general) is not an attractive career for young people, and therefore the consequence is the aging of the rural and farmer population [79, 192].

Agriculture is an obvious application area for robotics given the harsh weather working conditions, the repetitive, tedious and in some cases hazardous tasks (i.e. spraying pesticides and herbicides), in adverse conditions [53, 93]. However, the objective difficulties posed by the dynamic and unruly agricultural terrain on the one hand and the complexity ad hoc nature of agricultural tasks on the other, have, so far, limited the large scale application of robotics in agriculture [53].

Pre-programmed, completely automatic operation of an agricultural robot in the field would be, of course, the option of choice when available. It is not always possible –and it might be a moving target: as robotic and related information and communication technologies (ICT) progresses, there will always be more complicated agricultural tasks and terrains to tackle. Robotics in agriculture are considered to be a field application domain, because they have the relevant characteristics as identified by Murphy [123]: (a) the robots are subject to unpredictable environmental effects may impair platform and perceptual capabilities, and (b) robots are primarily extensions of humans; that is, doing what a farmer would do in the physical environment.

Within the framework of this study, I give the following definition when referring to "robotics in agriculture" as follows: *Robotics for agriculture is considered the domain of field systems able to autonomously perform coordinated, mechatronic actions, on the basis of processing of information acquired through sensor technology, with the aim to support professional farmers in performing agricultural tasks*.

This research provides a different approach for using the robot as a supplement rather than replacement of the farmer. Teleoperation - keeping the human in the loop - introduces the human capabilities of perception, auditory, anticipation, and pattern and motion recognition to a robotic system in the remote worksite. Its advantages include the human's perception skills [65, 105] and the robot's accuracy to carry out tedious tasks repetitively and consistently has a serious limitation: the farmer must be kept busy, if in more comfortable circumstances, and it remains to be seen if the savings in efficiency, comfort and health are worth the cost and effort.

In this dissertation, the focus is on semi-autonomous operation, which implies that the robot to some degree operates autonomously, however in some operations it requires human intervention. The human operator is not co-located with the robot and therefore some kind of a user interface is needed to enable the user to interact with the robot. Research questions associated with this problem include: 1) how should the farmer guide the robot's operation (moving along a pathway, grape clusters identification, spraying), 2) what is an appropriate user interface, 3) how should it be designed and 4) how should its usability be measured?

### 1.2. Research objectives

The objective of this dissertation is to study the design and evaluation aspects of a user interface that supports human-robot interaction, for semi-autonomous agricultural spraying robots. The research is applied towards the specific task of vineyard spraying. Different aspects related to the user interface design and evaluation that can enhance human-robot interaction are investigated within this thesis including:

A. Theoretical contributions related to development of: 1) a framework for semi-autonomous robot modes of operation, and 2) a taxonomy of user interface guidelines / heuristics.
B. Design, implementation and experimentation related to: 1) custom transformation of a robotic platform into a piece of agricultural machinery, the AgriRobot sprayer, 2) studies and experiments with the design aspects of user interfaces for robot tele-operation and tele-manipulation for the specific tasks of navigation, target identification and spraying, and 3) development and evaluation of suitable interfaces with enhanced HRI awareness to the farmer to effectively tele-operate a semi-autonomous vineyard robotic sprayer.

### 1.3. Research Significance

Rising labor costs, shortage of young farmers and of skilled agricultural workers, and the drudgery of the manual work required in the field, are among the main problems in modern agriculture. At the same time, agriculture is struggling to ensure food availability, food safety and cope with an increased demand for affordable, high quality products.

Mechanization of agriculture, with the use of tractors, combine harvesters among others, has helped both in lessening the difficulties of work and in increasing productivity. However, Bochtis, et al. [32] explain that "*only marginal improvements to the effectiveness of modern agricultural machinery are possible.*" ; this is directly related to the size and weight of modern machinery and the biological and environmental constrains in the field.

With the current advances in engineering, sensing and actuating technologies, along with the developments of information and communication technologies, another "helping hand" for these problems could be the use of robotic technology. Using robots for agricultural tasks in the field sounds obviously promising to carry out repetitive, tedious and hazardous tasks in adverse conditions. This can be accomplished by the introduction of already existing, robotic technology [53] that can augment the farmer's capabilities to carry out repetitive, hard, tedious, and most importantly in some cases dangerous for their health, agricultural work.

Robots are perceptive machines that can be pre-programmed to carry out various agricultural tasks such as weeding, spraying, harvesting et cetera [52]. Robot use can help by reducing the cost of production which derives from increased labor costs and the observed shortage of laborers, and reduce the drudgery of the manual labor, while at the same time raise the quality of fresh produce [51]. Farm mechanization in the past century usually took the form of machinery that is driven by humans and although work on such machinery is far easier than work without them, it is still hard and dangerous. The use of robots to carry out agricultural tasks, which can either be automated [50] or remotely guided [3], leaves the intelligence to humans who are in a more comfortable environment (i.e. office), instead of being outside in the field (i.e. driving a tractor).

An agricultural machinery operator is required to perform two basic functions simultaneously [86], steering the tractor and operating the agricultural machinery. As opposed to industrial robots, which operate in controlled environments, agricultural robots are challenged by several complexities related both to robot navigation in the field and the agricultural task at hand [51]. Such difficulties derive from the fact that robot moves on a loosely structured environment i.e. moving on unstructured and unpredictable terrains, and from task uncertainties such as, dealing with highly variable objects (e.g., fruit, leaves, branches) which differ in size, shape, color, and shading which are located at random locations and may vary (in size and color) even at the same plant [53]. For example, fruit harvesting, using autonomous robotic technology is still problematic mainly due to difficulties in detecting, reaching, grasping and detaching the crop from the plant [117]. Even though farmers are trying to “train” the trees to grow and follow a trellis, so as to have fruit-crops on the same level, one cannot do much, simply because of plant physiology and plant genetics [70, 176]. The problem of the non-standard and non-uniform location of the crops, the variability of crop size, shape and color - even within the same population due to the different stages of development leading to different stages of flowering and harvesting, as shown in Figure 1 - is still hard for harvesting robots to handle [12]. The handling of often delicate fruit crops, the limitations of identifying the crop due to obstacles such as leaves, tree branches, shading, limited lighting, are only but few of the challenges that the autonomous robots must address when harvesting crops [117].

*Figure 1. Crops location and colour of different varieties (issues with lighting and shading)*
*Left: Grape clusters variability in color due to lighting and shading conditions, Right: Strawberries with different size, color and maturity stages (blossom, unripe and ready to be harvested strawberries on the same plantation).*

Timing and seasonality is another factor of great importance in agriculture. There is an optimum time to perform certain agricultural tasks from planting through to harvesting crops. For example, pruning in vineyards usually takes place in winter while harvesting takes place between later summer and early autumn [176]. If one performs a task too early or too late, this has an implication on the yield and/ or quality of the crop which is affected.

In addition, agricultural robots work 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). In the case of agricultural robotics, autonomous navigation is much more challenging [111, 192] compared to other indoor robotic applications, like museum robot guides [59], or household robots [63] and outdoor application like search and rescue [151]. This is attributed to the fact that agricultural robots have to move through a rough, uncontrolled and unpredictable environment [53] including slopes, hills, rocks, plant rows, irrigation pipes, other agricultural equipment, laborers, harsh weather conditions, and more, some are shown in Figure 2. As such, several sensors and cameras are required to assist a robot while navigating in the field [51, 168]; this will be further discussed later in chapters 4 and 6.


*Figure 2. Various obstacles in the robot's pathway*

In the case of robot teleoperation, i.e. controlling robots from a distance [55], there is a human "behind" the robot, who directs 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. Fong, et al. [65] stated that "*teleoperation can be significantly improved if humans and robots work as partners.*" Semi-autonomous robots and human-robot interaction provide a promising alternative that could overcome the aforementioned limitations of fully autonomous agricultural robots.

### 1.4. Research contribution and innovations

This dissertation endeavors to systematically study the design and evaluation aspects of the user interface that supports human-robot interaction, for semi-autonomous agricultural robots focusing specifically on a robotic vineyard sprayer.

A **definition of a formal framework for semi-autonomous mode of operation is presented**. This formal framework brings out **human-robot interaction theoretical issues and more practical issues specific to the user interface design framework**. These are presented in Chapter 4 along with **a methodological approach presented to transform a robotic platform to a semi-autonomous agricultural robot sprayer**. The technical descriptions of the spraying platforms are provided in detail. How the robot functional and operational specifications were elicited, is also documented.

Based on the literature review, **a taxonomy of user interface guidelines/heuristics for mobile robot teleoperation was developed. Several user interfaces were designed, developed and implemented. Their usability was evaluated in laboratory and field experiments**. These **findings provide a proof-of-concept for semi-autonomous robots in agriculture and the importance of human-robot collaboration**. Additionally, the results show that **HRI awareness and situation**

**awareness are key concepts in tele-operation and tele-manipulation of field robots in agriculture**.

This dissertation interpolates material from several papers by the author [2-6]. The following is a bibliographical list, in chronological order, **of published work in conference proceedings and refereed journals**, which I submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy:

### *1.4.1 Journal publications*

i. Adamides, G., Christou, G., Katsanos, C., Xenos, M., and Hadzilacos, T., "Usability Guidelines for the Design of Robot Teleoperation: A Taxonomy," in *IEEE Transactions on Human-Machine Systems, vol. 45, no. 2*, pp. 256-262, April 2015.

ii. Adamides, G., Katsanos, C., Parmet, Y., Christou, G., Xenos, M., Hadzilacos, T., and Edan, Y., “HRI usability evaluation of input/output devices and concurrent views presented for a teleoperated agricultural robot”, in *Applied Ergonomics*, p. 15. (in process)

iii. Adamides, G., Katsanos, C., Constantinou, I., Xenos, M., Hadzilacos, T., and Edan, Y., “Design and development of a semi-autonomous agricultural vineyard sprayer – Human-Robot Interaction Aspects”, in *Journal of Field Robotics*, p. 29. (in process)

### *1.4.2 Conference proceedings*

i. Adamides, G., Berenstein, R., Ben-Halevi, I., Hadzilacos, T. and Edan, Y. “User interface design principles for robotics in agriculture: The case of telerobotic navigation and target selection for spraying,” In *Proceedings of the 8th Asian Conference for Information Technology in Agriculture, vol. 36*, 8p, Sep. 2012.

ii. Adamides, G., Katsanos, C., Christou, G., Xenos, M., Kostaras, N. and Hadzilacos, T. “Human-robot interaction in agriculture: Usability evaluation of three input devices for spraying grape clusters,” In *Proceedings of the EFITA/WCCA-CIGR Conference Sustainable Agriculture through ICT Innovation*, 8p, Jun. 2013.

iii. Adamides, G., Katsanos, C., Christou, G., Xenos, M., Papadavid, G. and Hadzilacos, T. “User interface considerations for telerobotics: The case of an agricultural robot sprayer". In *Proc. SPIE 9229, Second International Conference on Remote Sensing and Geoinformation of the Environment (RSCy2014), 92291W*, 8p, Aug. 2014.

iv. Adamides, G., Christou, G., Katsanos, C., Kostaras N., Xenos, M., Hadzilacos, T. and Edan, Y. "A reality-based interaction interface for an agricultural teleoperated robot sprayer". In *Proceedings of the Second International Conference on Robotics and Associated High-Technologies and Equipment for Agriculture and Forestry (RHEA 2014) New trends in mobile robotics, perception and actuation for agriculture and forestry*, pp. 367-376. May 2014.

v. Adamides, G., Katsanos, C., Xenos, M., Hadzilacos, T., and Edan, Y. "Heuristic usability evaluation of user interfaces for a semi-autonomous vineyard robot sprayer*"*. In *Proceedings of the Fifth Israeli Conference on Robotics (ICR 2016)*, 5p, April 2016.

### 1.5. Dissertation structure

This dissertation is organized in five chapters. Each chapter is organized as follows: I begin with a general overview about the chapter objectives and continue with the literature review and previous work in the specific area. This is followed with my own contribution and work and I conclude with findings and main contributions.

Following Chapter 1 "*Introduction*", in Chapter 2 "*Literature review*", I present the scientific background on the four research topics that guide this dissertation: agriculture, robotics, human-computer interaction, and human-robot interaction. Chapter 3, "*Methodology*", provides an overview of what and how was done throughout this work. In Chapter 4 "*Design and development of a semi-autonomous agricultural robot sprayer*", I present the work done to transform a robotic platform to an agricultural robot sprayer and a formal framework, defining the semi-autonomous mode of operation and the developed user interface. In Chapter 5 "*A taxonomy of HRI usability heuristics*", I present a systematic approach to develop a taxonomy of usability heuristics for robot teleoperation. All experiments - laboratory based and field experiments - are presented in Chapter 6 "*HRI Usability Evaluation: Field and Laboratory Experiments*". Specifically in this Chapter 6, I present the research methodology and main results of each experiment conducted during this time.

This dissertation concludes with Chapter 7, in which I document the main findings and summary of the most significant contributions. I also present a generalization of this work and suggestions for future research directions.

# Chapter 2. Literature Review

**Chapter overview**

The main objective of this chapter is to elaborate on the scientific background and present to the reader the state of the art in the areas related to this dissertation. The first section describes research concerning agriculture which is the application area. The second section briefly touches upon robotics, as the solution proposed, followed by the challenges of agricultural robotics and specific literature review for spraying robots. The third section describes research in human-computer interaction issues associated with user interfaces and usability evaluation methods. This brings us to the last section where I elaborate on human-robot interaction and related research issues on user interfaces for mobile field robot teleoperation.

## 2.1. Agriculture

Agriculture is a practice that has helped in the development of the humankind since ancient times [180]. Bareja [16] uses the following to define the term “agriculture”: “*the art and science of growing plants and other crops and the raising of animals for food, other human needs, or economic gain.*” I abide with this definition because a lot of creative skill and scientific knowledge has to go into the production of food from crops and livestock from the natural resources of our planet. It is no surprise then that farmers, even though they have to work hard and under harsh conditions in the field, they love working with cultivating the earth for crop and with animal production. Agriculture is not just the one of the most ancient professions; it is also the source of food for humankind.

According to the Food and Agriculture Organization (FAO), of the United Nations (U.N.) “*food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life.*” [185]. This means that there should be adequate resources to produce sufficient quantities of food to feed the world population, which according to FAO will reach 9.1 billion by 2050 [60]. Borlaug [141] is often called as the father of the ‘green revolution’ because of his efforts, to make developed countries self-sufficient in wheat production, through plant genetic improvements. Particularly, he developed semi-dwarf, high-yield, disease-resistant wheat varieties.

Climate change [82], limited land and water resources [8], the observed shortage of agricultural laborers [86], and farmers' aging [79] coupled with the hardness of agricultural work [52], increases the burden of producing more agricultural products with limited resources and environmental constraints.

Agricultural mechanization, precision agriculture, plant genetic improvements and other related practices are employed to optimize production of crops and cereals for food security and food safety. Automation in agriculture, mechanization and agricultural engineering, has been a major force for increased agricultural productivity in the 20th century [91, 116, 135]. While the number of farms and labor declined dramatically (in OECD countries) since the last century, the number of machinery and chemicals used in agriculture has increased, leading to an increased farm output. In fact, according to Huffman and Evenson [91] the aggregate United States farm output was "*... about 5.5 times larger in 1990 than in 1890*". At the same time, Oshima [135] concluded that mechanization in agriculture, along with the increased farm productivity (attributed to improved technologies), has driven most of the workers away from agriculture to manufacturing.

Advances in technology played an important role to the swift progress in the mechanization of agricultural practices. Of great importance were the tractors, combine harvesters, and other agricultural machinery which have significantly increased productivity while at the same time alleviated the drudgery of manual work in the farm. For example, one person involved in agricultural production, produces enough food and fiber for 128 persons, whereas a century ago without mechanization, this ratio was merely one to eight [116]. Yet, despite the increased agricultural productivity, given the world population growth, the aging of farmers, the limited land and water resources, and the migration of young people from rural areas to urban areas, there is still need to further intensify crop and livestock production in order to secure food availability [61].

Precision agriculture or smart agriculture or precision farming, emerged in the late 1980s with the aim to help farmers make informed decision-making. Precision agriculture utilizes technologies such as the Global Navigation Satellite System (GNSS), geographic information systems (GISs), weather stations and soil sensors, information technologies and most recently big data, the internet of things and robotics [97, 175], in order to optimize crop yields per unit of farming land. In other words, precision agriculture is leading farmers to a resource-efficient, environmental friendly, enabling them to optimize agricultural production by applying the right treatment, in the right place at the right time; thus leading to sustainable agriculture [34]. According to the American Society of Agronomy [9], sustainable agriculture is one that "*over the long term, enhances environmental quality and the resource base in which agriculture depends; provides for basic human food and fiber seeds; is economically viable; and enhances the quality of life for farmers and the society as whole.* " Even though precision agriculture technologies have been around since the 1990s, adoption of these technologies by farmers has been relatively modest [44]. The farm operator characteristics that were found to be important determinants of precision agriculture adoption were: well educated, computer-literate operators of large farm size row crops farms.

Similarly to precision agriculture technologies adoption by farmers, to date the use of robotics in agriculture is also less extensive than one would expect given on one hand the tediousness of agricultural tasks, such as planting, spraying or harvesting, and on the other hand the observed technological advances in the development of highly accurate and reliable systems and embedded sensors.

## 2.2. Robotics

Robots have been in use since the late 1940s [106] in various industries. Initially robots were found in manufacturing [136, 157], and later in mining [81], space [31, 148], medicine [77], agriculture [51], entertainment [165], search and rescue [13, 39, 151], and social robots (i.e. the Honda humanoid robot [89]). Reasons for using a robot include: a) to reduce the safety risks for humans, b) alleviate the hardness of the work-at-hand, and c) to take advantage of their accuracy and reliability. The etymology of the word itself, robot means literary "hard work" (from the Czech word robota), as coined by author Karel Čapek in the 1920s [106].

Their application in the industry can be characterized as successful given that, for humans working in an industrial setting, the work is usually monotonous and tiresome while at other times hard. The industrial robots are programmed to operate autonomously in a fully controlled environment and they do so with great precision and speed [167].

Recent developments both in hardware and software paved the road to the introduction of service oriented robots that are used in hospitals [114], in museums [45, 191], and even at home. The coexistence of professional and service robots with humans creates the need for better and improved interaction techniques [167].

Industrial robots, operate in fully controlled and set environment, which is often engineered in such a way that minimizes the amount of autonomy required, and this according to Thrun [167] is "*a key ingredient of the commercial success of industrial robotics".* Moreover, industrial robots, mining robots, medical robots, even space robots are used throughout the year. In contrast, the seasonal nature of agriculture and farming makes the use of robotic equipment necessary during certain seasons often for few days or even hours per year [52, 159]. A tractor can be used for many agricultural tasks i.e. plowing, planting, weeding, harvesting, etc. [87]. Robots are still costly and until they go to mass production [80], one cannot afford to purchase a robot that would do just one task, for some time during the year.

### 2.3. Agricultural robots and sprayers

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 [12] 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 complicate the development of completely autonomous systems [137]. Regarding cost, it is reasonable to expect that the cost of robotics in general will continue to decrease because: a) general progress in electronics and mechanical devices tends to reduce their cost and increase their performance and b) widespread use of agricultural robots will create larger demand and therefore lower prices. In fact, Pedersen, et al. [138], showed three autonomous systems (grass cutting, weeding, and field scouting) that are economically viable given certain technical and economic assumptions. Thus, the key to a more widespread use of robotics in agriculture is its effectiveness. 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 [12] or spray [27] more than this percentage of crops.

Blackmore, et al. [29] and Pedersen, et al. [137], posit that small autonomous intelligent agricultural vehicles, capable of working 24x7 are more efficient than the larger traditional tractors.

Research on autonomous agricultural robot sprayers has been carried out in the past decades [160]. A comparative list with specific results, the plant application and sensor technology used, is presented by Berenstein, et al. [27]. Furthermore, Berenstein, et al. [27] 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. In addition, agricultural robot sprayer teleoperation can reduce human exposure to pesticides, thus reducing safety concerns and medical hazards [27].

Autonomous robotic sprayers have been developed for weed control in field applications [28, 33, 36, 68, 101, 121], trees in orchards [102, 131], vineyards [1, 27], and greenhouse applications [73]. A comprehensive review of agricultural automation systems including field machinery, irrigation systems, greenhouse automation, animal automation systems, and automation of fruit production systems can be found at Edan, et al. [53].

Selective spraying pesticides towards the targets, using a robot sprayer could reduce up to 30% of the pesticide (spraying material) while detecting and spraying 90% of the grape clusters [27]. Today, vineyard spraying is achieved by spraying uniform amounts of pesticides along the vineyard rows without considering low density foliage, which requires less pesticide, or gaps between the trees. Moreover, the grape clusters are concentrated in a 0.5m strip along the vineyard row. Although only the grape clusters should be sprayed, existing approaches spray the entire strip, resulting in excess amounts of unnecessary pesticides sprayed in the environment. The Agricultural Engineering Yearbook estimates that it is possible to reduce pesticide use by 10%–30% just by using sprayers that can avoid spraying between trees [99].. Semi-autonomous robot (including controlling robots from a distance [55] is a promising alternative that could overcome the aforementioned limitations.

The spray equipment widely used in vineyards (and other cultivations) includes hand-held spray guns, tractor-based boom sprayers, air-assisted spray machines, and recently robot sprayers. According to Buchanan and Amos [37], in order for spray machines to be efficient, they ought to provide acceptable pest control at the lower cost. They also explain that hand-held spray guns, can be highly effective, however they are slow (a farmer carrying the spray tank walking in the field) and costly [37]. A comprehensive overview of vineyard sprayers, including selecting and setting up a sprayer, selecting components, calibration and coverage testing can be found at Furness, et al. [67].

Targeted spraying (either on foliage or on grape clusters) can be used for chemical grape berry thinning and for increasing berry size of grapes. For example, Gil, et al. [70], Weaver [176] and Winkler, et al. [182], explain various means of improving grape quality by applying plant growth regulators, such as gibberellins. In this case hand-held sprayers would be inefficient as it would require long hours to manually walk through, select and target spray the entire vineyard. Other means of sprayers such as boom sprayers, air-assisted spray machines, and aerial spraying, that were described above are not suitable for selective targeted spraying.

Precision agriculture techniques were also applied for spraying orchard trees. Wellington, et al. [179] used two applications that use probabilistic approaches in interpreting radar sensor data and generating tree models in an orchard environment. An automated tree inventory and more precise spraying was achieved using the aforementioned applications on an agricultural vehicle with range sensors and a mounted GPS. Endalew, et al. [56] studied and modelled the effect of tree foliage on sprayer airflow in a peer orchard. They used a 3-D computational fluid dynamics model with an integration of the 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.

Recently Guzman, et al. [80] presented VINBOT, a robot for precision viticulture. VINBOT is an autonomous mobile robot capable of capturing and analysing 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 vigour maps.

Zaidner and Shapiro [192] proposed a data fusion algorithm for fusing localization data from various robot sensors for navigating an autonomous system in the vineyard.

Research related to human-robot collaboration for target recognition in a site specific sprayer has been developed by Berenstein [21] including target detection algorithms [27], target marking techniques [23], a remote interface for human-robot collaboration [26], collaboration levels between the human and the robot [25], and an adjustable diameter spraying device [22].

### 2.4. HCI and user interfaces

Human-computer interaction (HCI) is a discipline concerned with the design, evaluation and implementation of interactive computing systems for human use and with the study of major phenomena surrounding them [87].

Interacting with a computer system is something that we have learned to do in some cases with ease, in other cases with some effort. The first interaction era between computer operators and computers were through punch cards, followed by the second generation that used command line instructions and later on, in the 1970s at Xerox PARC the Graphical User Interface (GUI) also known as WIMP (Windows, Icons, Menu, Pointing Device) interaction emerged. It is still the dominant interaction style to date [172]. This 3rd generation of user interfaces gained their popularity mainly due to their ability to give to the user the feeling of direct manipulation (DM) [92, 158]. With the GUIs the users can interact with the digital world and have immediate feedback of their actions to the digital world [92, 158]. Direct manipulation techniques gave a more natural interface and thus minimized the cognitive load of the user, made it easy to learn and remember how to use. Instead of memorizing commands and their syntax, users are using the mouse to select the command from menus. van Dam [172] defines post-WIMP interfaces as "*interfaces which contain at least one interaction technique not dependent on classical 2D widgets such as menus and icons.*" They should involve all senses in parallel, natural language communication and multiple users. Post-WIMP interfaces allow users to directly manipulate objects, as if in the real world, thus increasing the realism of interface objects and allowing users to directly interact with them. Post-WIMP interfaces or the Reality-Based Interaction style (RBI), can help reduce the gulf of execution and gulf of evaluation [95]. Examples of post-wimp interaction styles [95, 172] are: virtual, mixed and augmented reality, tangible interaction, ubiquitous and pervasive computing, handheld or mobile interaction, perceptual affective computing as well as lightweight, tacit or passive interaction. According to Jacob, et al. [95]"*all of these interaction styles draw strength by building on user's pre-existing knowledge of the everyday non-digital world.*"

The RBI themes, identified by Jacob, et al. [95] are: 1) Naive Physics (NP) - people have common sense knowledge about the physical world. Concepts like gravity, friction, velocity, the persistence of objects and relative scale, 2) Body Awareness and Skills (BAS) - people have an awareness of their own physical bodies and possess skills for controlling and coordinating their bodies. For example VR applications allow users to move from one place to another within a virtual environment simply by walking on a special track or treadmill [191], 3) Environmental Awareness and Skills (EAS) - People have a sense of their surroundings and possess skills for negotiating, manipulating and navigating within their environment. People also develop skills to manipulate objects in their environment, such as picking up, positioning, altering, and arranging objects either virtually or physically, and 4) Social Awareness and Skills (SAS) - People are generally aware of others in their environment and have skills for interacting with them. These include verbal and non-verbal communication, the ability to exchange physical objects and the ability to work with others to collaborate on a task. It is evident how important these four themes are in this dissertation, specifically in the case of human-robot interaction. The robot operator needs to be aware of the robot's surrounding, so as to be able to perform an action (EAS, SAS). The operator, through such an interface, also needs to have a sense of "feeling" the force, i.e. to cut a branch (force-feedback) (Naïve Physics, BAS). For a farmer it is "natural" to use eye-hand coordination to select which crops to select and cut. When performing this action it is also "natural" to have immediate visual feedback. These are some characteristics that can help reduce both the gulf of execution and the gulf of evaluation. In the next paragraphs we present some examples, from the literature review, of post-WIMP interaction styles currently used in HRI systems.

An operator when interacting with a robot manipulates not the digital world but rather the real world. According to Norman [130], interaction in the real world has seven stages: it begins with identifying the goal, forming the intention, specifying an action, executing the action, perceiving the state of the world, interpreting the state of the world and evaluating the outcome. I consider these seven stages very important especially in the design of a user interface because they take into account two fundamental concepts of interaction: execution and evaluation. To execute something one first has to set a goal of what they want to accomplish, then form the intention to do it, and then translate it into a set of commands, and take the actions sequence to execute it. Once something is executed in the world we evaluate the result; so one first perceives what has happened in the real world, then interpret that perception to see if it matches our expectation, and lastly compare it with our intentions and goal.

### *2.4.1 User interface modelling techniques*

In order to improve remote robot teleoperation Goodrich, et al. [74] presented an ecological interface paradigm, based on Gibson's notion of affordances [69]. The goal is to provide the operator with appropriate and sufficient information such that the observed affordances of the remote robot match the actual affordances in the environment. Goodrich, et al. [74] presented a 3-D augmented-reality interface which integrated three design principles: 1) present a common reference frame, 2) provide visual support for the correlation of action and response, and 3) allow an adjustable perspective. They concluded that such system helps to reduce the cognitive processing required to interpret the information from the robot cameras and sensors and make decisions.

Drury, et al. [46] explain why traditional modelling techniques used in HCI, such as the Goals, Operations, Methods, and Selection rules (GOMS), differ in HRI. They explain that 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). In their paper [46] they have shown how GOMS can be used to determine the operator's workload and compare different user interfaces to model the operator's interaction with the robot.

Armato, et al. [11] adapted the Unified Modelling Language (UML), a graphical language, for modelling user interfaces for human-robot interaction. They argue that UML is a very simple and intuitive approach that can help roboticists to optimize the design of HRI interfaces, resulting in "*a more natural and effective interactions between human beings and robots*."

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 [94]. So, a usability issue is anything that can affect in a negative way the user experience.

There are many sources of data that can be used to derive usability issues, but the most common ones include user performance data, verbal expressions of confusion or dissatisfaction (e.g. from think-aloud protocol [20]), behavioral/physiological data (e.g. from eye-tracking [142]) and reports from usability experts (e.g. heuristic evaluation

[128]). Usability issues are often prioritized based on severity schemes [126] that take into account various factors (e.g. impact on user experience, predicted frequency of occurrence, impact on business goals) in an attempt to increase their usefulness for the next design iteration. Various metrics can be reported, often grouped by severity level, based on usability issues such as: (1) Total number of unique usability issues, (2) Average number of usability issues per participant, (3) Percentage of participants that encountered a specific issue, (4) Number of unique issues for each task, and (5) Percentage of participants encountering an issue for each task.

Each of the aforementioned usability metrics can be used to derive a composite overall usability score. Such metrics are commonly used to decide if the current design has been improved compared to the previous one. Typically, a composite overall usability score is derived by multiplying each raw usability score with a weight, and then the products are summed and divided by the sum of the weights. Single Usability Metric (SUM; [146]) is a composite metric that combines task completion, task time, error counts per task and post-task satisfaction into a usability score for each task or into an overall usability score for the evaluated system.

Nielsen explain that "*Heuristic evaluation is a "discount usability engineering" method for evaluating user inter-faces to find their usability problems*" [126]. Discount because a small number of evaluators, usually 3 to 7 [124], is enough to evaluate the usability of a user interface against a list of heuristics (the usability principles). Clarkson and Arkin [42] present a list of heuristics to evaluate human-robot interaction. They created an initial list HRI heuristics, modified that list based on pilot studies, and finally validated the modified list against existing HRI systems. Adamides, et al. [2] presented a taxonomy of design guidelines for robot teleopeation. The guidelines were grouped into eight categories (the heuristics): platform architecture and scalablity, error prevention and recovery, visual design, information presentation, robot state awareness, interaction effectiveness and efficiency, robot environment/surroundings awareness, and cognitive factors.

### 2.5. User performance metrics

Performance metrics rely on observed, goal-directed user behavior [169]. Such metrics are collected by monitoring and analyzing the behavior of representative users who are asked to perform a number of specific tasks, after using the evaluated system. Performance metrics can be used to evaluate the effectiveness and efficiency of the evaluated system. According to Tullis and Albert [169] metrics widely used in HCI include the following: (1) Task success, (2) Time on task, (3) Errors, (4) Efficiency, and (5) Leanability.

#### *2.5.1 Self-reported metrics*

Self-reported metrics provide information about userss' perceptions of the system and feelings related to their experience with it. They are used to provide quantitative estimations of either the whole user experience or specific elements of the user experience, such as perceived ease of use [166], perceived effectiveness, efficiency and satisfaction [110], system usability scale [35], and others.

#### *2.5.2 Number of users required to collect usability metrics*

The number of participants required in a usability test to reliably identify usability problems is a much debated issue. Researchers [127] argue that five participants are enough to identify 80% of usability problems, whereas some others [163] argue that five partic-ipants are nowhere near enough. Based on their accumulated experience as practitioners, Tullis and Albert [169] argue that five participants per significant class of users is enough to reveal the most important usability issues if the evaluation scope is fairly limited (5-10 tasks) and the user audience is well represented. Lindgaard and Chattratichart [113] argue that "*investing in wide task coverage is more fruitful that increasing the number of users*".

### 2.6. HRI usability and metrics

Clarkson and Arkin [42] declared, what makes a robotic interface effective is no different than what makes anything else usable, be it a door handle [130] or a piece of software [119]. Depending on the type of application one attribute might be more critical than another. For example, the interface should prevent user errors, and if a user makes a mistake, the user interface should allow for its rectification. However this is not always possible; consider the following, in contrast to undoing a "Cut" operation in a word processor, a "Cut" command to prune a tree through a teleoperated robot cannot be undone.

Huang, et al. [90], provided a concept of contextual metrics for unmanned systems. Their model characterizes the unmanned system performance by (a) the mission to be carried out, (b) the environment where the system operates, and (c) the characteristics of the system itself.

Olsen and Goodrich [132] explain that the goal of human-robot interaction design is to reduce interaction effort without diminishing task effectiveness. Goodrich and Olsen [75] explain that during remote teleoperation there are two interaction loops: one when the human operator interacts with the robot via an interface, and a second one when the robot interacts with the real world environment via an autonomous mode. In order to tackle limitations that are produced either from the user interface or from the autonomous mode of the robot, they proposed seven principles for efficient human robot interaction (also presented in Chapter 4). Olsen and Goodrich [132] proposed metrics for measuring the effectiveness of human-robot interactions. They conclude that the key to HRI effectiveness is increasing the neglect tolerance of the robots and reducing the interaction effort of the interface. Specifically, they explain that being able to determine when the interaction effort has been reduced by a new user interface design is critical to the development of new types of HRI systems.

Steinfeld, et al. [164] proposed five task oriented metrics for mobile robots that can be performed by a wide range of tasks and systems be it pure teleoperation, semi-autonomous or full autonomy (1) Navigation, (2) Perception, (3) Manipulation, (4) Management, and (5) Social. In this research we are particularly interested in the first three metrics. With regards to *navigation*, effectiveness is measure by how well the task was completed (i.e. coverage area, percentage of navigation tasks completed successfully, obstacle avoided et cetera). Perception is the process of making inferences about objects in the environment based on feedback by robot sensors. Potential measures include *passive perception* (i.e. interpreting sensor data) and *active perception* (i.e. control of pan and tilt of a camera, control of robot movement in the field). *Efficiency* in HRI measures the time required to complete the aforementioned tasks.

Usability, user experience, social acceptance and social impact are factors that have considerable impact of the interaction between humans and robots [177]. Specifically, in HRI usability is usually measured as performance/effectiveness and efficiency. Indicators for usability include the following: (1) *Effectiveness* “the accuracy and competences with which users achieve specified tasks” (e.g. success rate or task completion rate), (2) *Efficiency* “the resources expended in relation to the accuracy and completeness with which the users achieve goals” (e.g. rate or speed at which a robot can accurately and successfully assist humans), (3) *Learnability* “how easy can a system be learned by novice users?” (e.g. familiarity, consistency, predictability, simplicity, (4) *Flexibility* “describes the number of possible ways how the user can communicate with the system", (5) *Robustness* "novice users will produce errors when collaborating with robots, thus a usable HRI system has to allow the user to correct faults on his/her own" (e.g. error preventing, responsive and stable), and (6) *Utility* "how an interface can be used to reach a certain goal or to perform a certain task".

### *2.6.1 HRI usability evaluation of teleoperated robots*

Human-robot interaction user interface design and usability evaluation has been studied extensively in search and rescue operation robotics [47-49, 104, 151, 190]. Yanco, et al. [190] explains that HCI evaluation methods can be adapted for use in HRI as long as "*they take into account the complex, dynamic, and autonomous nature of robots*." Drury, et al. [49] compared two interface categories, a video-centric and a map-centric, to find which category provides better situation awareness. They found that a map-centric interface was more effective in providing good location and status awareness. The video-centric interface was more effective in providing good surroundings and activities awareness. Scholtz, et al. [151] evaluated HRI awareness in several urban search and rescue (USAR) competitions. They studied human-robot interfaces to determine what information helps operators to successfully navigate the robots in disaster areas and locate victims. Based on their study the developed guidelines for information display for USAR robots.

Weiss, et al. [178] distinguishes between direct and indirect HRI interaction to explain that in direct interaction humans and robots have direct contact interaction while in indirect HRI interaction this occurs via a remote control. With regards to HRI usability, they explain that it the user should be able to identify whether an interaction issue occurred because of the user interface or the robot. Based on results from their user study they found that problems were assigned to the GUI or to the robot "*in an almost equal distribution*." They state that, this may the case because "*traditional usability measures only give a limited insight on the degree of usability*", and that this approach should be rethought.

For robot teleoperation, Randelli, et al. [144] conducted an experiment to evaluate three control input interfaces, the Wiimote controller, a joypad implemented on a Wiimote device, and a PC keyboard. They found that the least effective interface was the joypad. The Wiimote controller and the PC keyboard were significantly better in terms of collisions, compared to the joypad, while the Wiimote was not statistically significant with respect to the keyboard. Participants' of the experiment reported that "the PC keyboard was the best interface for controlling the robot in narrow spaces, whilst the Wiimote was too reactive for hard terrain difficulty conditions". Randelli, et al. [144] conclude that tangible user interfaces such as the Wiimote are too sensitive for much cluttered areas. Similarly, Velasco, et al. [173], evaluated three approaches to control teleoperated mobile robots: (a) the PS3 gamepad, (b) a PC keyboard, and (c) a mobile phone interface. They conclude that the PS3 controller was adequate for handling the mobile robot, the keyboard was efficient, while the phone interface was the most intuitive. Eliav, et al. [55] examined two innovative methods to control a Pioneer 2DX mobile robot, a touch screen and using hand gestures. They found the touch screen to be "superior in terms of both objective performance and its perceived usability" while the hand gesture method was more complex.

Chen, et al. [41] explain that effectiveness of remote driving can be compromised because of limited field of view. Specifically, drivers may have more difficulty in judging the speed of the vehicle, time-to-collision, perception of objects, location of obstacles, and the start of a sharp curve. Peripheral vision is important for lane keeping and lateral control. Wider field of view is particularly useful in tactical driving tasks when navigating in unfamiliar terrain. In order to successfully navigate in remote environment, the operator of the robot needs to have a good sense of orientation both globally and locally. For robots with extended manipulators (e.g. sprayer wand), cameras could be placed on top of the end-effector (e.g. sprayer nozzle) in order to capture the remote scene egocentrically or on the body of the robot to provide for exocentric view of the end-effector [145]. Furthermore, according to Casper and Murphy [39] multiple camera viewpoints enhance remote perception. Providing a wide viewing angle enables to minimize distortion and to easier cope with the difficulties of locating objects in the field of view of a teleoperated robot [55]. Chen, et al. [35] conclude that multimodal controls and displays have a great potential in robotic teleoperation tasks.

Martins and Ventura [115] proposed a visualization/control system of their search and rescue RAPOSA robot, based on a Head Mounted Display (HMD). They concluded that the user's depth perception and situational awareness improved significantly when using the HMD. Moreover, their efficiency and effectiveness was improved: users were able to reduce the operation time by 14% and successfully identify more objects when using the HMD. By contrast, Lichtenstern, et al. [112] reported several users' inconveniences with HMD and higher overall task load index, which however tended to decrease over the course of time.

### 2.7. Human-Robot Interaction

Human-Robot Interaction (HRI) is "*the field of study dedicated to understanding, designing, and evaluating robotic systems for use by or with humans"* [76]. Fong, et al. [65] defined HRI as "*the study of the humans, robots and the ways they influence each* other". Human-Robot Interaction, is a multi-disciplinary field in which researchers from areas of robotics, human factors, cognitive science, natural language, psychology, and human-computer interaction, are working together to understand and shape the interactions between humans and robots. Communication and interaction can be separated into *remote interaction* and *proximate interaction*. In remote interaction the human and the robot are not collocated and are separated in space or even in time. In proximate interaction the humans and the robots are collocated. Goodrich and Schultz [76] explain that remote interaction with a mobile robot is often referred to as *teleoperation* and remote interaction with a physical manipulator is referred to as *telemanipulation*. In this dissertation the focus is on remote interaction both with a mobile robot and its physical manipulator (sprayer).

Thrun [167] explains that human-robot interactions differ according to the kind of robot (industrial, professional, service) and similarly the human-robot interaction is different. For example, in industrial robotics the human-robot interaction is limited because industrial robots usually do not interact with people; rather they carry out pre-programmed commands, whereas professional (i.e. surgical robots) and service (i.e. tour guide robot), that come in contact with humans, require human-centered interfaces. Thrun [167] also makes a distinction between direct and indirect interaction: (a) indirect interaction is the one where the operator sends commands to the robot and the robot executes, and (b) direct interaction in which the information flow is bidirectional.

Yanco and Drury [186] introduced a taxonomy of HRI, and later [187] an updated taxonomy, for classifying human-robot interaction. The taxonomy was developed to describe the human/robot relationship and robot characteristics that affect human interaction. Their updated taxonomy categories, a description of each category and the possible classifications, are presented below:

- **Task type:** The task to be accomplished sets the tone for the system's design and use, so the task must he identified as part of the system's classification. Task type also allows the robot's environment to be implicitly represented.
- **Task criticality:** It measures the importance of getting the task done correctly in terms of its negative effects should problems occur. Criticality is a highly subjective measure, so to counteract this problem, they have defined a critical task to be one where a failure affects the life of a human. Possible classifications are high, medium and low.
- **Robot morphology:** Robots can take many physical forms and people react to robots differently based upon their appearance. Possible classifications are anthropomorphic, zoomorphic and functional.
- **Ratio of people to robots:** The ration of number of humans over the number of robots.
- **Composition of robot teams:** Are the robots in a team of the same type or are they different? Homogeneous teams lend themselves to a single interface more naturally, as opposed to heterogeneous teams.
- **Level of shared interaction among teams:** The possible combinations of single or multiple humans and robots, acting as individuals or as teams. Possible teams are: ([one human, one robot]; [one human, robot team]; [one human, multiple robots]; [human team, one robot]; [multiple humans, one robot]; [human team, robot team]; [human team, multiple robots];[multiple humans, robot team]).
- **Interaction roles**: The roles a human may have when interacting with a robot including Supervisor; Operator; Teammate; Mechanic; and Bystander.
- **Type of human-robot physical proximity:** In the case where humans and robots are collocated, depending upon their tasks and the purpose of the human's interactions with robot(s), robots and people may need to interact at varying interpersonal distances. Possible classifications are: avoiding; passing; following, approaching and touching.
- **Decision support for operators:** The type of information that is provided to operators for decision support such as available sensors; provided sensors; sensor-fusion; and pre-processing.

- **Time/Space taxonomy:** Depending if the humans and robots are using computing systems at the same or different time and same or different place. Possible classifications are: Time [Synchronous; Asynchronous], Space [Collocated; Non-collocated].
- **Autonomy level / Amount of intervention:** The amount of intervention required for controlling a robot is one of the defining factors for human-robot interaction. There is a continuum for robot control ranging from teleoperation to full autonomy.

### *2.7.1 HCI vs HRI*

Initially, Fong, et al. [65] and later Scholtz [150], argued that HRI is fundamentally different from Human-Computer Interaction (HCI) and Human-Machine Interaction (HMI). HRI differs from HCI and HMI because robots are complex, dynamic systems, which exhibit autonomy and cognition, and operate in a changing and real world environment. Scholtz [150] identifies differences between HRI and HCI in the types of interactions (interaction roles), the physical nature of robots, the number of systems a user may be called to interact with simultaneously, and the environment in which the interactions occurs. Similarly, Goodrich and Schultz [76] separate communication and interaction into two general categories: 1) Remote interaction: the human and the robot are not collocated and are separated spatially or even temporally (for example the mars rover are separated from earth both in space and time [148]), and 2) Proximate interaction: the humans and the robots are collocated (for example tour guide robots among museum visitors [59]).

On one hand Yanco and Drury [189], maintain that HRI is a subset of HCI, since robots are considered as computing systems. Their argument is supported by the definition provided by Hewett, et al. [88]: “Human-Computer Interaction is a discipline concerned with the design, evaluation and implementation of interactive computing systems for human use and with the study of major phenomena surrounding them.” On the other hand, Dautenhahn and Saunders [45] explain that, in interacting with computers we are used to waiting for the computer to complete a task, or we may take time to respond. Even a computer game can be paused, replayed etc. Interacting with computers is highly predictable and based on procedures and routines. In Human-robot interaction one typically does not have those options. Human-robot interaction takes place in real-time; we can't 'stop' an interaction, we have to react in real-time similar to how we interact with people.

### *2.7.2 Human-robot collaboration*

The ultimate goal for human-robot interaction is to develop and use efficiently robots such that human skills and abilities become more productive and effective, such as freeing humans from routine or dangerous tasks [143]. Interaction, the process of humans working collaboratively with robots to accomplish a goal, emerges from the confluence of autonomy, information exchange, teams, and task shaping. For a fully autonomous robot the interactions may consist of high level supervision and direction of the robot with the human providing goals and with the robot maintaining knowledge about the world, the task and its constraints.

Fong, et al. [66] proposed the collaborative control model for teleoperation. In this model, the robot and the human work as a team to perform tasks and achieve common goals. This model encompasses aspects of human-robot interaction, dialogue and switching between different levels of automation. Fong, et al. [65] identified the key issues in building collaborative control systems: 1) self-awareness (i.e. knowing what it can do and the human can do), 2) self-reliance (i.e. capability to maintain its own safety), 3) dialogue (i.e. two-way communication via a user interface), and 4) adaptation (i.e. be able to adapt to different operators). Endalew, et al. [56] demonstrated the collaborative control model with multimodal operator interfaces and semi-autonomous control with three interaction tools: a Personal Digital Assistant (PDA), gestures, and a haptic device. The human operator issues commands through queries and the robot responds, creating a dialogue between the two towards accomplishing their task. To improve the operator’s awareness of the remote site they had displays with information from various sensors (ladar, sonar, stereo vision). The limitation of the GestureDriver was that it assumes the operator is in the robot’s field-of-view, which is not always possible in teleoperation missions. The HapticDriver greatly improved obstacle detection and avoidance, but its limitation was that it provided only 2D force information. The PDADriver was easy to deploy and provided different user interface modes: map, video, command and sensor.

Several cooperative systems have been developed. Sheridan [156], divides automation into ten levels; from fully autonomous to pure teleoperation. Bechar and Edan [18] defined four human-robot collaboration levels for target recognition tasks in unstructured environments: (a) HO—the human operator unaided, detects and marks the desired target—compatible with level 1 on Sheridan's scale; (b) 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 scale; (c) 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 scale; and (d) R—the targets are marked automatically by the system (robot) – compatible to Sheridan 10 level. Analytical [19] and simulation [24, 133] analyses demonstrated that collaboration of human operator and robot can increase detection rates and decrease false alarms when compared to a fully autonomous system. Implementation on an operational robotic sprayer [21] indicated similar improved performance when a human collaborated with the robot.

Melamed, et al. [117] presented a simulation model for human-robot cooperation for sweet pepper harvesting in greenhouses. Specifically they examined different human-robot combinations for the harvesting process and evaluated different logistics processes using a simulation model. Preliminary results showed the advent of collaboration.

Fong, et al. [65] makes a distinction between direct HRI and teleoperation. In direct HRI the robot and the human interact directly (e.g. proximal /physical interaction). If the robot(s) and the human(s) working together to accomplish some task/ goal, are not collocated (i.e. in time and /or space), then the interaction is called teleoperation [65, 156].

### *2.7.3 Human-Robot Interaction Awareness*

Drury, et al. [47] provided the standard definition for HRI awareness: "*Given one human and one robot working on a task together, HRI awareness is the understanding that the human has of the location, activities, status, and surroundings of the robot; and the knowledge that the robot has of the human's commands necessary to direct its activities and the constraints under which it must operate*."

Tullis and Stetson [171] emphasized that in safety-critical domains, the critical actions must be decided by human operators, not by robots. In order for humans and robots to collaborate in an effective manner there must be adequate situation awareness. HRI awareness is related with situation awareness, the understanding a user has when controlling a machine (i.e. teleoperation of a remote robot). Endsley [57] defines situation awareness as "*the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future*." We will adopt these two definitions and adapt them in the case of agricultural HRI awareness later in Chapters 2, 3, and 4.

HRI awareness depends upon the level of autonomy of the robot. Drury, et al. [47] identified the following human roles in the context of robotic systems: supervisor, operator, mechanic, teammate, and bystander. In this dissertation the main focus is on the *operator* role and the *user interface* which they use to communicate with the robot.

### *2.7.4 Teleoperation and collaborative control*

Teleoperation is the mode of operation where an operator, directly controls a robot [147]. Burke, et al. [38] posits that robot teleoperation is the primary mode of operation in human-robot systems and characterizes it as "*irreplaceable*." Teleoperation allows an operator at one location to perform a task at some other location [40].

The negative effect of teleoperation is that the operator actually has to do physical work in order to perform work at the remote site. Furthermore, teleoperation can become challenging due to poor communication between the two sites; the quality of the human-machine connection may cause noise and signal transition delays.

Teleoperation is not easy to implement and its performance is significantly limited by the operator's capacity to construct mental models of the remote environment and to maintain situation awareness [98]. It's imperative then that the user interfaces between humans and robots to support the operator to obtain and maintain sufficient awareness of the robot's location and surroundings.

### *2.7.5 User interfaces for robot teleoperation*

Hainsworth [81] refers to the requirements for developing a user interface for teleoperation of mining robots. The main features of the human-robot interaction interface include video displays (for navigation and surveillance), a control console, and the graphical user interface which presents environmental data, robot status indicators, vehicle operator parameters, and data about the status of the communication cable handling the system. According to [81] this is sufficient feedback for the operator to enable appropriate control of the remote mining robot.

However, in robot teleoperation it is quite difficult for the operator to navigate the robot while doing other tasks (i.e. target identification and spraying). This difficulty is related to the limited field-of-view and the loss of situational awareness. Limited field-of-view has been attributed to negatively affect locomotion, spatial awareness, and perception of self-location [98]. With respect to situational awareness, the challenge is to design a human-robot interface such that it presents the information from the remote environment and the perceived affordances [130] of the environment matches the actual affordances [69], thus enabling the operator to perceive, comprehend, and anticipate this information from the remote environment.

Murakami, et al. [122] developed a system for teleoperation of agricultural vehicles. The developed user interface provided a map using Google Maps, an indicator of the vehicle location in the field, and included an omnidirectional camera to give feedback to the operator about obstacles around the robotic vehicle and about its activities.

Monferrer and Bonyuet [120] mentioned five topics that should be considered when designing user interfaces for teleoperated robots in a cooperative environment. These are: (a) visible navigational aids, to help the operator guide the robot from point A to point B (i.e map, compass, etc.), (b) customized reference data, meaning give them the ability to point and select in the area where it executing the task (i.e. mark and spray the grape clusters of a vineyard), (c) chat channels, especially when more than one robots are under the command of a human operator, to exchange and record messages and notes about the environment, the progress report etc. (i.e. use of voice commands or writing down a record of the executed task, etc.), (d) redundancy with critical data, that is informing the operator about critical data by using discrete sound messages, and (e) attractive data presentation, present the information in aesthetically pleasing manner and user-friendly way.  They also discussed particularly issues related to virtual reality user interfaces:(a) the use of natural landmarks for reference about certain actions, (b) virtual route, depict the path that that robot has followed towards the target, (c) special marks,  that will improve the awareness of the operator regarding the remote environment, and (d) virtual – reality synchronization, meaning objects in the virtual world must be synchronized with the one in the real world, to provide a meaning interaction. Communication latency should be taken in account to avoid data misinterpretation.

Chen, et al. [41] reported the challenges that an operator faces while interacting with a robot located at a remote site. The situation awareness (denoted SA) of the operator may be reduced and this has negative consequences on the effectiveness of the mission [49, 57, 58, 181]. Teleoperation can also be a challenge due to the increased cognitive load of the user caused by the constant change of view/mode and the latency due to technological limitations [49]. To improve SA they propose the use of multimodal interactive user interfaces (tactile, aural, auditory, and visual).

Aracil, et al. [10] emphasized the use of visual aids, auditory aids, and tactile aids to enhance the awareness of the operator of the remote site where the robot is located. Vision gives the optical representation of shapes, colors, size and distance of various objects on which the robot will act. Through the robot cameras images of the remote site are sent back to the user to enhance their situational awareness. Auditory aids are of equal importance especially when we refer to telerobotics systems, since they attract the attention of the user without putting extra burden on the visual senses. Given that acoustic stimuli are 30-40ms faster that visual stimuli, they make them an ideal solution for sporadic messages or for danger warnings.

Teleoperation introduces the human capabilities of perception, auditory, anticipation, and pattern and motion recognition to a robotic system in the remote worksite. 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. Drury, et al. [49], explains that when the operator and the robot (who he/she tele-operates) are not collocated, good situation awareness (SA) is necessary. Endsley [57] defined SA as "*the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near* future." One way to accomplish a high level of situational awareness, is to allow the operator to view the worksite from an observer's perspective [181]. Endsley [57] provided general principles for designing for SA. Drury, et al. [47] presented a framework for human-robot interaction awareness and later Drury, et al. [49] proposed the LASSO technique (location awareness, activity awareness, surroundings awareness, status awareness, and overall mission awareness) for analyzing HRI situation awareness.

Designing usable human-robot interactions supports operators to perform complex tasks [55, 181]. There are two paradigms for human-robot interaction: teleoperation and supervisory control [76]. Teleoperation indicates operation of a robot from a distance

[156]. Sheridan [155] explains that "*a teleoperator is a machine enabling a human operator to move about, sense and mechanically manipulate objects at a distance*." Supervisory control refers to a system architecture where a human operator is responsible for overseeing (supervising) robots acting autonomously providing feedback based on sensor data through a data-processing station [140]. Sheridan and Verplank [154] proposed ten levels of automation that are "*assumed to apply to most man-computer decisions."* In this chapter, the focus is on semi-autonomous operation, which implies that the robot to some degree operates autonomously, however in some operations it requires human intervention. The human operator is not co-located with the robot and therefore the need for some kind of a user interface, for the user to interact with the robot.

HRI researchers have examined the human-robot aspects of interaction in great detail, including the design and evaluation of such user interfaces [42, 46, 48, 78]. In HRI, a user interface with natural mappings and affordances could reduce the learning curve and help learnability [7], by giving to the user the ease of identifying the correct function/method to accomplish a goal. According to Norman [130] the fundamental principles for designing for people are: (a) provide a good conceptual model and (b) make things visible. Natural mapping between controls and actions will help users understand what is expected of them to perform (related to gulf of execution). According to Norman [129], gulf of execution is the difference between the intentions of the users and what the system allows them to do or how well the system supports those actions.

Feedback is sending back to the user information about what actions had already been done to understand what results has been accomplished by his/her actions (related to gulf of evaluation [129]). In other words the users become aware of their actions and evaluate whether they had accomplished the indented goal. For example, Hainsworth [81] refers to the requirements for developing a user interface for teleoperation of mining robots. The main features of the HRI interface include video displays (for navigation and surveillance), a control console, and the GUI, which presents environmental data, robot status indicators, vehicle operator parameters, and data about the status of the communication cable handling system. According to Hainsworth [81] this is sufficient feedback for the operator to enable appropriate control of the robot.

This dissertation will focus on the topic of user interfaces for human-robot interaction and especially for the case where the human and the robot are not collocated, by taking into consideration recent developments of the new generation interfaces [95] with the aim to provide for natural, efficient and effective HRI. I am particularly interested in the interaction of humans with remote mobile robots, meaning the human is located at a site and the robot at another remote site.

# Chapter 3. Research Methodology

**Chapter Overview**

The main objective of this chapter is to present to the reader a general overview of the methodology followed towards achieving the objectives set in this dissertation:

(A) Theoretical contributions: 1) a framework for semi-autonomous mode of operation, and 2) a taxonomy of user interface design guidelines, and

(B) Design, implementation and experimentation: 1) the transformation of a robotic platform to an agricultural robot sprayer, 2) the design and development stages of the user interfaces, and 3) evaluation methodology followed during the HRI usability evaluation of the user interfaces.

The details about the proposed framework, the robot transformation and the user interface characteristics will be presented in Chapter 4. The details of the taxonomy will be presented in Chapter 5, while the HRI usability evaluation experiments will be explained in Chapter 6.

## 3.1. Levels of autonomy framework

A theoretical formal framework of the levels of autonomy of the spraying robot is proposed. The assumptions are presented, followed by the formal statements. 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 tele-operated). The details of this framework and an example implementation are presented in Chapter 4.

## 3.2. A taxonomy of HRI user interface design guidelines

To develop the proposed taxonomy of user interface design guidelines for teleoperated field robots, the first step was collecting and reviewing studies on user interface design guidelines, heuristics and principles specific to HRI. The emphasis was on mobile field robot. Searches were performed on three online bibliographic databases: ACM's digital library, IEEE's Xplore, and Elsevier's ScienceDirect. The search queries included general keywords, such as robot teleoperation, usability heuristics, robot teleoperation user interface, and specific keywords such as HRI user interface guidelines, HRI user interface principles, HRI usability, and HRI heuristics.

The collected papers were inspected based on reading of the abstract and conclusions, duplicates were eliminated, leaving 127 papers to read. Papers that presented teleoperated HRI without mentioning user interface guidelines, principles and heuristics, or papers that evaluated aspects of user experience experimentally or qualitatively were excluded. The resulting 38 papers with overlapping heuristics, user interface guidelines, or design principles for the development or evaluation of HRI were reduced to 17 papers, from which 70 HRI-specific user interface design guidelines, heuristics and principles were extracted.

The articles that were selected for the development of the HRI taxonomy included heuristics, guidelines and principles for the user interface design development or evaluation of HRI for mobile field robots.

The two primary methods of performing card sorts, open and closed [162] were used to produce the proposed taxonomy. In an open card sorting exercise, participants are given cards with no pre-established groupings and are asked to sort cards (i.e., user interface guidelines) into groups and name those groups. In the closed card sorting alternative, participants are given cards along with an initial set of primary groups and are asked to place the cards into these pre-established groups (in our case those derived from the open card sorting). Closed card sorting can be conducted for consensus building or as additional user research [162]. Here, the closed card sorting survey served to test our categories and refine the proposed taxonomy. The details of this work is discussed in Chapter 5.

### 3.3. Agricultural robot sprayer

The research was applied in the context of two research projects AgriRobot[1] and SAVSAR[2]. In this chapter I present the methodology followed for the design, development and testing of these two agricultural robot sprayers and their evolvement.

In both projects The Summit XL and the Summit XL HL mobile platforms by Robotnik (http://www.robotnik.eu) were used. These platforms are medium-sized, high mobility all-terrain robot, with skid-steering kinematics based on four high power motor-wheels. These platforms were selected because they can move both indoors (i.e.

[1] https://www.youtube.com/watch?v=w3Inq5tBxa8
[2] http://www.savsar.gr

greenhouse) and outdoors (i.e. agricultural field) in a variety of field applications. Their control architecture is open-source and modular, based in ROS[3].

The design of the robots 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 [3].

With AgriRobot v1 (Figure 3), 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. Following, informal interviews and documentation of their observations, several modifications on the platform resulted to an improved version.

[3] http://wiki.ros.org/Robots/SummitXL

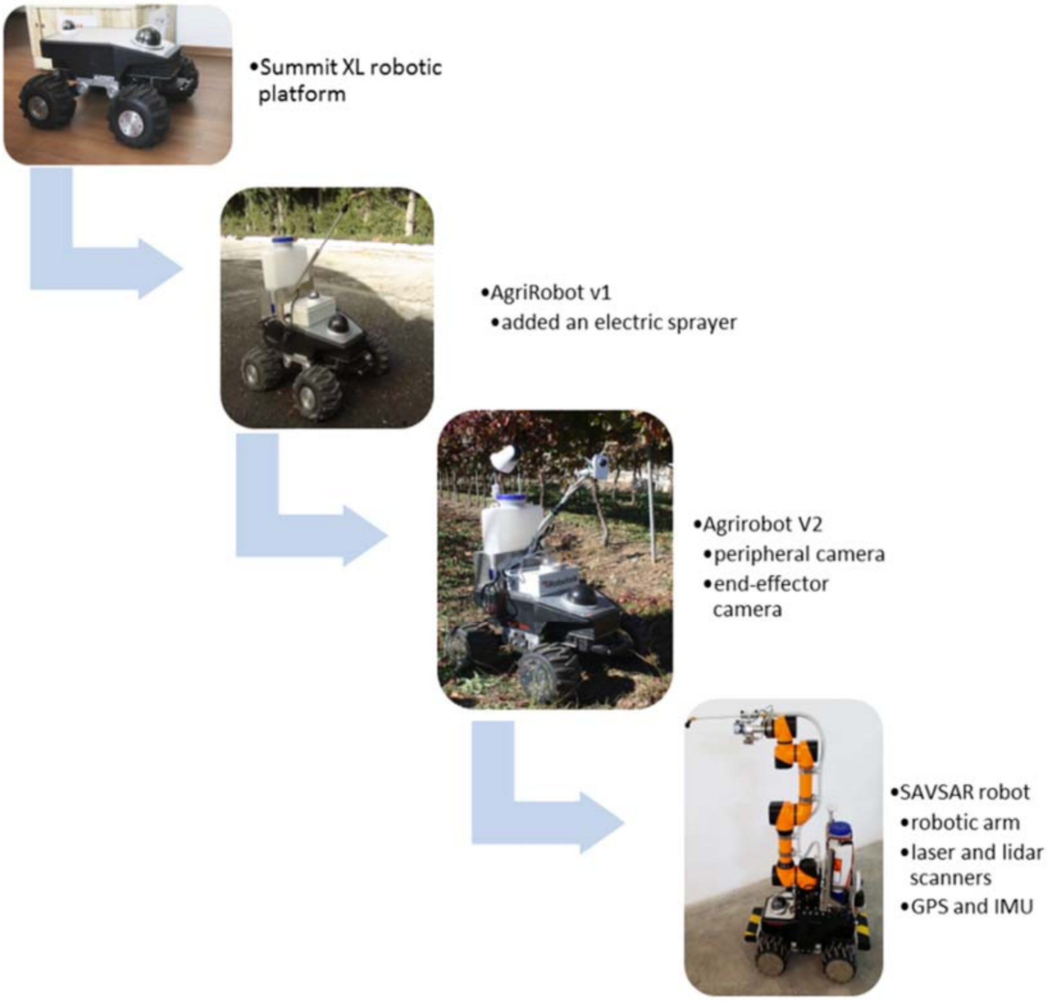



*Figure 3. Development stages of the robot sprayer*

The upgraded version (Figure 3 - Agrirobot v2) 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 solutions were provided: 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, also two solutions were provided: a) connecting the output device to digital glasses and b) teleoperating the robot from inside an office environment.

The following HRI taxonomy (Table 1) was assumed in this dissertation for the semi-autonomous agricultural robot sprayer, based on the HRI taxonomy proposed by Yanco and Drury [187].

*Table 1. HRI taxonomy for the agricultural robot sprayer*

| **Category** | **Description** | **Classification** |
|---|---|---|
| Task type | There are three tasks to be executed in this HRI: guiding the robot in the vineyards, identifying targets to spray, and the actual spraying task | [Navigation (robot path guidance), Target Marking/ Identification, Spraying] |
| Task Criticality | Given that in robot navigation there is a possibility to harm either the robot or bystanders or the vines, the task criticality is High. For the target identification and spraying the criticality is set to low. | [High, Low] |
| Robot morphology | Mobile robotic platform with spraying capabilities | [Functional] |
| Ratio of people to robots | One human operator and one robot sprayer | [1:1] |
| Composition of robot teams | Same robot | [Homogeneous] |
| Level of shared interaction | One human operator and one robot sprayer | [one human, one robot] |
| Interaction roles | During Autonomous mode the human is acting as supervisor. During the teleoperation mode the human is acting as Operator. During the semi-Autonomous mode the human is acting as teammate. | [Supervisor, Operator, Teammate] |
| Type of human-robot physical proximity | The human and the robot are not collocated | [Avoiding] |
| Decision support for operators | Battery level, camera and sonar sensors | [Provided sensors] |
| Time/Space taxonomy | Human and robot operate at the same time in different locations | [Time (Synchronous), Space (Non-collocated)] |
| Autonomy level / Amount of intervention | There is a continuum for robot control ranging from teleoperation to full autonomy | [Autonomy+Intervention= 100%] |

In the specific case of the AgriRobot sprayer, the navigation task (robot path guidance) was performed in tele-operation mode, while the target marking/

identification and spraying tasks were performed in autonomous or semi-autonomous mode.

### 3.4. User interface design and development stages

In the case of our agricultural robot sprayer, teleoperation (Figure 4) features: (a) an operator interface, incorporating a master input device (PS3 gamepad/mouse/keyboard) that the operator uses to communicate the system, (b) a slave output device (the robot sprayer) that performs the operator's commanded actions at the remote site, and (c) a communication scheme (web-based user interface over Wi-Fi) between sites.

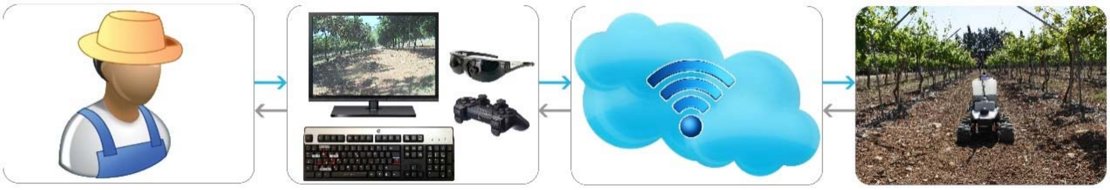


*Figure 4. Robot teleoperation scheme in the case of the agricultural robot sprayer*

For the design and development stages of the robot's tele-operated user interface an iterative method was followed as shown below in Figure 5. The value (benefits) of iteration in a usability engineering process is illustrated by a commercial development project analyzed by Karat [100]. This methodology was applied in the context of the two research projects (AgriRobot and SAVSAR).

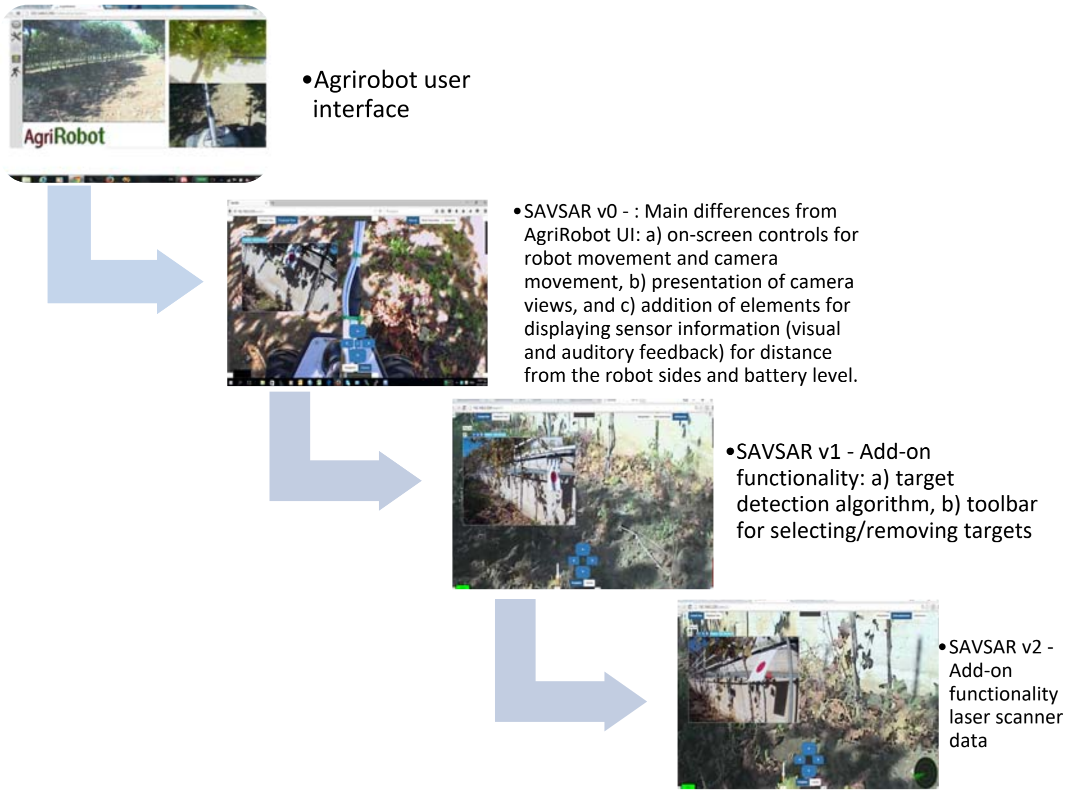



*Figure 5. User interfaces development stages*

### 3.5. HRI User interface usability evaluation

The usability of the different combinations was evaluated by measuring users' interaction effectiveness, interaction efficiency and overall satisfaction. This was measured separately for each task.

For the robot navigation task, effectiveness was operationalized by the total number of collisions: fewer collisions, is more effective. Steinfeld, et al. [164] suggest using the number of obstacles avoided as one of the effectiveness metrics in the navigation task. However, the number of actual collisions was used because in an agricultural field one might avoid obstacles along the path but still have collisions i.e. with tree stems or support poles on the side (Figure 6).

*Figure 6. Top: Collision of the AgriRobot on a vine tree stem;*
*Bottom: Collision on a fruit-collection box (obstacle) and on a pole*

For the spraying task, effectiveness was measured by the number of grape clusters sprayed[4], a binomial random variable with 24 trials (total number of targets).

Similarly, efficiency was operationalized by time on task, which is the overall time required to complete the whole teleoperation task (navigation and spraying). Subjective assessment of usability (i.e. perceived usability), was measured by the post-task 10-item System Usability Scale (SUS) [15, 35, 103]. 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

[4] The variable *Percent_Completed* does not follow the normal or Poisson distributions. It is actually a binomial random variable with 24 trials. So instead of analyzing *Percent_Completed* we analyzed the variable *Sprayed* and took into account that 24 attempts were done by a participant in each condition.

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. [14] associated SUS scores with a 7-point grading scale of perceived usability (from worst-imaginable to best-imaginable). Tullis and Stetson [171] compared various post-study questionnaires and found that SUS yields the most consistent ratings.

### *3.5.1 Field experiment methodology*

***Experimental design***

This study was a 2x2x2 repeated measures experiment; the *type of screen output* (PC screen and Head Mounted Display,HMD), *the number of views* (single view and multiple views), and the *type of robot control inputs* (PS3 gamepad and PC keyboard). The three factors were within subject factors, each one of the 30 participants experienced the eight interaction modes (combinations) in random order to keep the unsystematic variation to a minimum [62]. The participants were asked to use the aforementioned eight different interaction modes to perform the two tasks.

Usability of 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. Steinfeld, et al. [164] suggests using the number of obstacles avoided as one the effectiveness metrics in the navigation task. However, the actual number collision was selected for this metric, because in an agricultural field one might avoid obstacles but still have collisions, i.e. with tree stems or support poles on the side. 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 operationalized by time[5] on task, which is the overall time required to complete the whole teleoperation task (path guidance and spraying). Subjective assessment of usability (i.e. *perceived usability*), was measured by the post-task 10-item System Usability Scale (SUS) [35]. Other factors that may affect the user

[5] The General Linear Model assumes that the dependent variable distributes normal. Time to event is known to be a non-normal skewed to the right distribution. A common solution to overcome this problem is to transform the dependent variable so that the transformed variable will have normal distribution. The inverse transformation (1/time) was used.

experience were also examined, specifically the users' efficacy, immersion tendencies and task workload.

# Chapter 4. Design and development of a semi-autonomous agricultural robot sprayer

## Chapter Overview

The main objective of this chapter is to present to the reader a general overview of the work done, with respect to the design and transformation of an existing mobile platform into an agricultural robot sprayer. The hardware and software modules that must be installed onto the system are described, with particular emphasis on the user interface and related aspects for human-robot interaction awareness. In addition, a formal framework is developed for the robot autonomy levels, with the rules that describe the transition between them upon user intervention in the robot operation.

This thesis focuses on the aspects of the user interface, and how it should be designed [2], in order to be suitable for teleoperation of a mobile field robot while performing agricultural tasks. The spraying task is taken as the application.. A target-specific robotic sprayer can reduce the quantity of pesticides applied in modern agriculture and reduce human exposure to pesticides [27]. Semi-autonomous robot teleoperation is a way to enable targeted specific spraying. Figure 7 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.

*Figure 7. 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*

In the case of a semi-autonomous agricultural robot sprayer, 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 he/she decides to do so. Semi-autonomous operation requires an operator interface, incorporating a master input device that the operator uses to communicate the system any non-pre-programmed actions or when there is a need to intervene, a slave output device that performs the operator's commanded (or pre-programmed) actions at the remote site, and a communication scheme between sites. In the following section, I delve on semi-autonomous operations and how this was implemented in this work.

## 4.1. Transforming a mobile platform to an agricultural robot sprayer

***Overview***

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 I developed and implemented. Figure 8 is a schematic of the most advanced one.

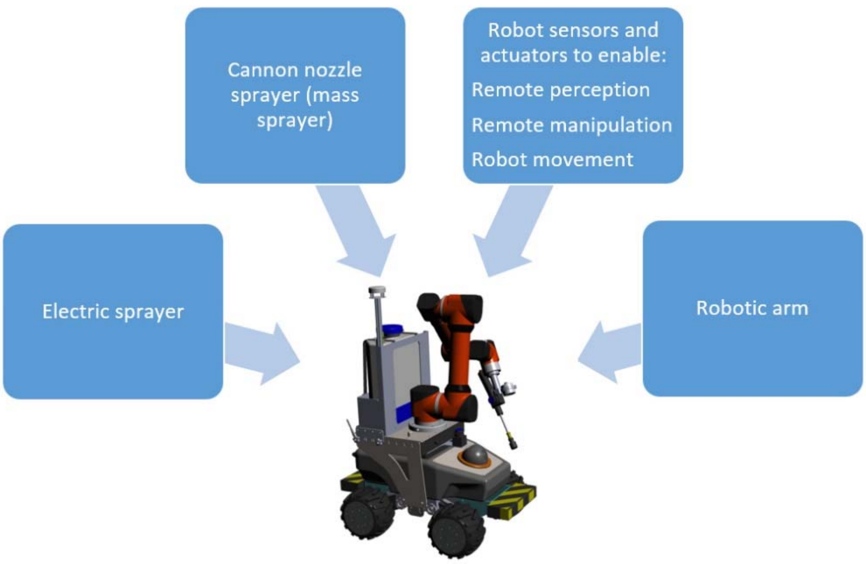



*Figure 8. Block diagram with modules to engineer a mobile robotic platform into a robot sprayer*

### *4.1.1 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 two previous R&D projects (AgriRobot and SAVSAR) partners' expertise. The requirements 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 $\geq 25kg$ allowing a meaningful spraying session
- Sufficient surface to install on it a sprayer tank and/or robotic arm (based on the size of an 18lt tank, at least 40x65 centimeters is required)
- Environment input devices such as cameras and microphones

***Sensors***

The agricultural robotic sprayer should be equipped with sensors for localization and navigation, 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:

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

***Inertial Measurement Unit (IMU)***

An appropriate IMU plus an Arduino-compatible processor, is part of the proposed solution. This IMU integrates: 6 Gyros, 3 Accelerometers, and 3 Magnetometers to provide information about the robot inclinations (Roll, Pitch, and Yaw). This is important to determine potential instability conditions, e.g. stop before the robot is climbing a too high slope. 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.

### *Cameras*

In semi-autonomous and remote teleoperation applications, the operator most of the times is not co-located with the robot in terms of time and space. To enable the user's remote perception, at least three cameras are needed to alleviate the restricted field-of-view effect (Chen et al., 2007) and provide the user with HRI awareness (Drury et al., 2003), especially if no laser scanners are available. In the experiments reported in Chapter 6, it was found that this (limited location and surroundings awareness) was true even when the operator was co-located with the robot.

The selected robotic platform provided two 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), and (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).

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 was moved at the back-top side of the robot to enable peripheral vision. A third camera, an AXIS M1025 HDTV 1080p network camera, was installed on the end-effector sprayer nozzle to give the spraying area visual feedback.

### *Laser scanners*

Two laser scanners should be used. 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 have the robot halted when it comes across an obstacle. In that way we can ensure that robot or humans/animals will stay safe. In addition, a 360 degree 2D laser scanner can perform 360o scans within a specified range.

The Lidar Sensor can produce 3D point cloud data that can be used in mapping, localization and object/environment modelling. 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.

The following table presents the two robot platforms which were transformed to robotic sprayers with their characteristics based on the above requirements.

*Table 2. AgriRobot and SAVSAR requirements characteristics*

<table>
<tr><th>Feature requirement</th><th>AgriRobot</th><th>SAVSAR</th></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td>All-terrain mobility</td><td colspan="2">Yes</td></tr>
<tr><td>Climbing angle</td><td colspan="2">45 degrees</td></tr>
<tr><td>Skid-steering</td><td colspan="2">4 high power motorwheels</td></tr>
<tr><td>Speed</td><td colspan="2">3 meters per second</td></tr>
<tr><td>Odometry</td><td colspan="2">Encoder on each wheel and a high precision angular sensor assembled inside the chassis</td></tr>
<tr><td>Battery autonomy</td><td colspan="2">5 hours</td></tr>
<tr><td>Pan-tilt-camera</td><td colspan="2">Yes</td></tr>
<tr><td>Additional cameras</td><td colspan="2">Yes</td></tr>
<tr><td>Electric sprayer</td><td colspan="2">Yes</td></tr>
<tr><td>Payload capacity</td><td>25kg</td><td>65kg</td></tr>
<tr><td>GPS</td><td>No</td><td>Yes</td></tr>
<tr><td>Sonar sensor</td><td>Yes</td><td>No</td></tr>
<tr><td>Laser sensor</td><td>No</td><td>Yes</td></tr>
<tr><td>Lidar sensor</td><td>No</td><td>Yes</td></tr>
<tr><td>IMU</td><td>No</td><td>Yes</td></tr>
<tr><td>Bumpers</td><td>Yes</td><td>Yes</td></tr>
<tr><td>Robotic arm</td><td>No</td><td>Yes</td></tr>
</table>

### *4.1.2 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: (a) increase the available input devices for robot control (PS3 gamepad and keyboard), and (b) increase the 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. The following keys were selected in the keyboard mode to control the robot based on the literature from video games [17] and HRI [78]: ‘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.

### *4.1.3 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. A next version (SAVSAR robot) of the agricultural robot sprayer, for selective targeted spraying, was designed to include a robotic arm with six degrees of freedom.

#### *Mass spraying*

To install a sprayer on the top cover of the mobile robot chassis, several modifications and adjustments are necessary. 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 in order to enable the electric sprayer to send the on/off switch command to the robot. The Modbus IO is an Ethernet (MODBUS) communication that has 8 digital inputs and 4 digital outputs which was connected directly onto the robot’s battery. The battery then is used to fumigate the device for its power. To control the On/Off switch of the sprayer one of the relay outputs was used. The switch is controlled through a PS3 gamepad button or the keyboard (spacebar).

***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 was used with a robotic arm in addition to the sprayer tank. The installed robotic arm is the OUR-1, a low-cost, light-weight, industrial Open Unit Robot. The manipulator has six joints, each with a degree 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.

## 4.2. Problems faced with the platform transformation and suggested solutions

Transforming a mobile robot to an agricultural robot sprayer was challenging due to several hardware, software and environmental constraints, and lack of experience (no previous work on robotics). In this section the problems that rose during the transformation of the robot and related software issues during the user interface development are detailed.

### *4.2.1 Hardware related issues*

*a. Robot cameras*

The Summit XL robotic platform came with two pre-installed cameras: on in the front of the chassis and another one on the top of the chassis. From the beginning of our attempts to tele-operated the robot through a user interface it was noticed that the placement of the camera on the top of the chassis needed to change and be relocated at the back-top (elevated) of the platform to enable peripheral vision. This was necessary as no laser scanner was installed on the platform and the sonars were not giving adequate (visual) feedback about the surroundings of the robot.

Once a sprayer nozzle was installed it was also obvious that a third camera was required to give feedback about the targets to be sprayed. So a third camera was installed on the top of the sprayer nozzle. Initially, a set of USB web-cameras were installed for peripheral and target view, however these were later replaced with Ethernet cameras as these were not affecting the processing power of the on-board computer inside the robot. The proposed solution, regarding the placement of cameras, is shown in Figure 9, below.

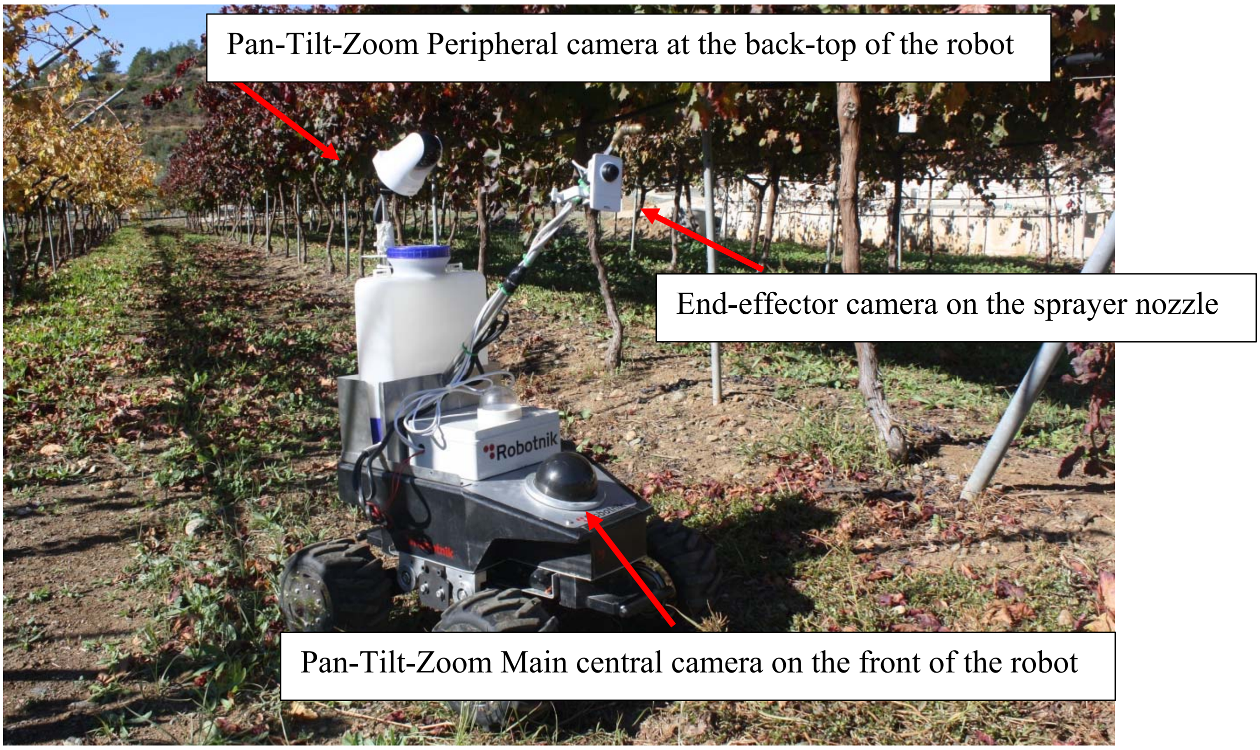



*Figure 9. Proposed solution for camera placement*

*b. Electric sprayer*

An electric sprayer was needed to transform the robot into an agricultural sprayer (Figure 10). Three things needed to be done towards this end: a) install a Modbus IO to transmit input/output commands, and b) purchase an electric sprayer, and c) design and install a case for the sprayer on top of the robot chassis. Since there was space available inside the robot to place the Modbus IO, a separate case was installed on top of the robot chassis along with the sprayer tank holder.

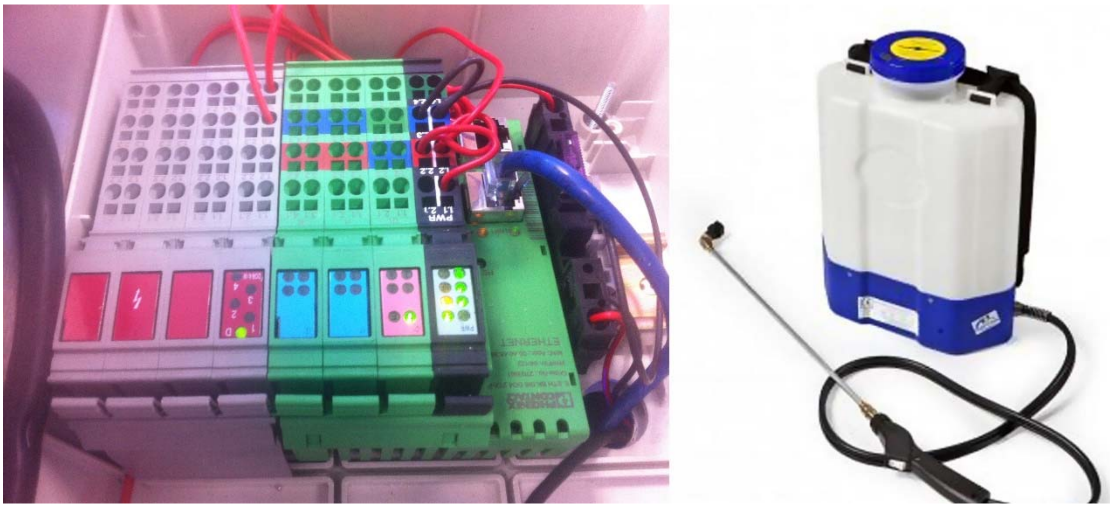


*Figure 10. Left: The MODBUS IO, Right: the Serena Electric sprayer*

After the first tests in the field, two problems were identified: a) due to the robot movement the elastic hose to the nozzle was punctured (see Figure 11), so it was reinforced with binding tape, and b) the cannon was stable and could not be enlarged or moved. To fix this second problem the solution proposed was to add a robotic arm with six degrees of freedom to enable the movement of the sprayer nozzle.

*Figure 11. Fractured hose problem - Left: friction caused the problem, Center: the actual problem water leakage, Right: problem fixed with reinforced binding tape*

### *c. Robot wheels*

The robot came with four rubber wheels with a soft foam inside (Figure 12). After using the robot for about a year in the field, it was noticed that the wheels were damaged. The soft foam was badly damaged and had to be replaced. The solution proposed by the Robotnik Company was to replace the entire set with an improved set of wheels with hard foam.


*Figure 12. Problem with robot wheels – Top-left: the damaged wheel, Top-right and bottom-left: the damaged inside soft foam (on the left, the original soft foam on the right); Bottom-right: the new set of wheels with hard foam inside.*

Other problems with regards to the robot platform transformation and with the operation of the robot cameras, the MODBUS IO, the PS3 gamepad configuration for spraying et cetera, were overcame with help and support from Robotnik[6] Automation S.L.L. in Spain.

### 4.3. Defining "semi-autonomous operation" for an agricultural robot

In this section a formal framework of the levels of autonomy of the robot is described, based on which the system architecture was designed. Rules describing the transition between the levels of autonomy when the user intervenes in the robot operation are defined. The framework determines (a) whether the current robot operation is pre-programmed ("robot-controlled") or directed on-line ("human-operator") and (b) the current level of autonomy (autonomous, semi-autonomous or tele-operated).

For the proposed formal framework of the levels of autonomy, the following definitions were adopted:

[6] http://www.robotnik.eu

*Robot Operation*: The robot may perform operations concurrently, such as moving, recognizing targets, spraying et cetera. Every operation has two modes: the manual (teleoperation) mode and the autonomous (pre-programmed) one.

*Manual mode*: Is the mode of operation where the current on-line user (operator) synchronously directs robot operations.

*Autonomous mode*: Is the mode of operation where the robot is acting autonomously, i.e. according to its pre-programmed instructions.

*Level of autonomy*: The current mode of operation that the robot operates (Autonomous, Semi-autonomous or Teleoperation).

### *4.3.1 Definition of the levels of autonomy*

Suppose we have a robot with N ($N \in \mathbb{N}$) different operations, each of which can be executed manually by the operator or autonomously as programmed by the robot. According to this assumption the following formal statements are defined:

*Statement 1*: If the robot has N operations in manual mode, then the robot is in manual level.

*Statement 2*: If the robot has N operations in autonomous mode, then the robot is in autonomous level.

*Statement 3*: If the robot has M ($M \in \mathbb{N}$) operations in manual mode, where $0 < M < N$, and the remaining N-M operations in autonomous mode, then the robot is in semi-autonomous level.

*Statement 4*: If one operation of the robot is changed, then the level of operation is redefined according to the above statements 1, 2 and 3.

*Statement 5*: If the user intervenes in an operation, then this operation automatically reverts to manual operation.

Based on these statements, the levels of autonomy of the robot, and who (at all times) has the responsibility of the decision making for the operations of the robot, are defined. Figure 13, illustrates the block architecture of the framework of the levels of autonomy. The framework is divided in the user robot level. Both levels are able to perform all operations at least trivially (e.g., if no navigation software is installed on the robot, the autonomous mode of navigation operation is “stay still”.)

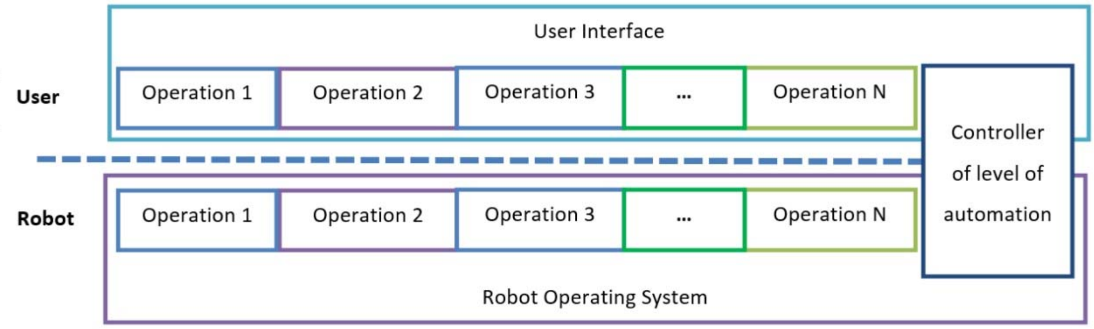



*Figure 13. Blog diagram: Architecture framework of autonomy levels*

### *4.3.2 Implementation of levels of autonomy*

The automation controller is responsible for the mode of each operation according to the user intervention. The implementation of this framework architecture is based on the client-server web model. The client is the user (browser) and the server is the robot. The client is running on a browser while the robot is running on ROS. For the SAARS implementation the following web technologies were used: JavaScript, HTML5 and CCS3 for the implementation of client operations; PHP, python and C++ for the implementation of robot operations. The openCV library was used for the implementation of the recognition algorithm (Berenstein et al., 2010). The communication between the user and the robot is supported via POST and GET actions.

Every operation can be done via user or via robot, separately. The user initially sets the default mode for each operation. If the user intervenes in an operation, when in autonomous mode, then the level automation controller transits the operation to manual mode. According to the proposed framework, if there is one operation in manual mode and one in autonomous mode then by definition, the robot is in semi-autonomous operation. This process is presented in a state diagram in Figure 14.

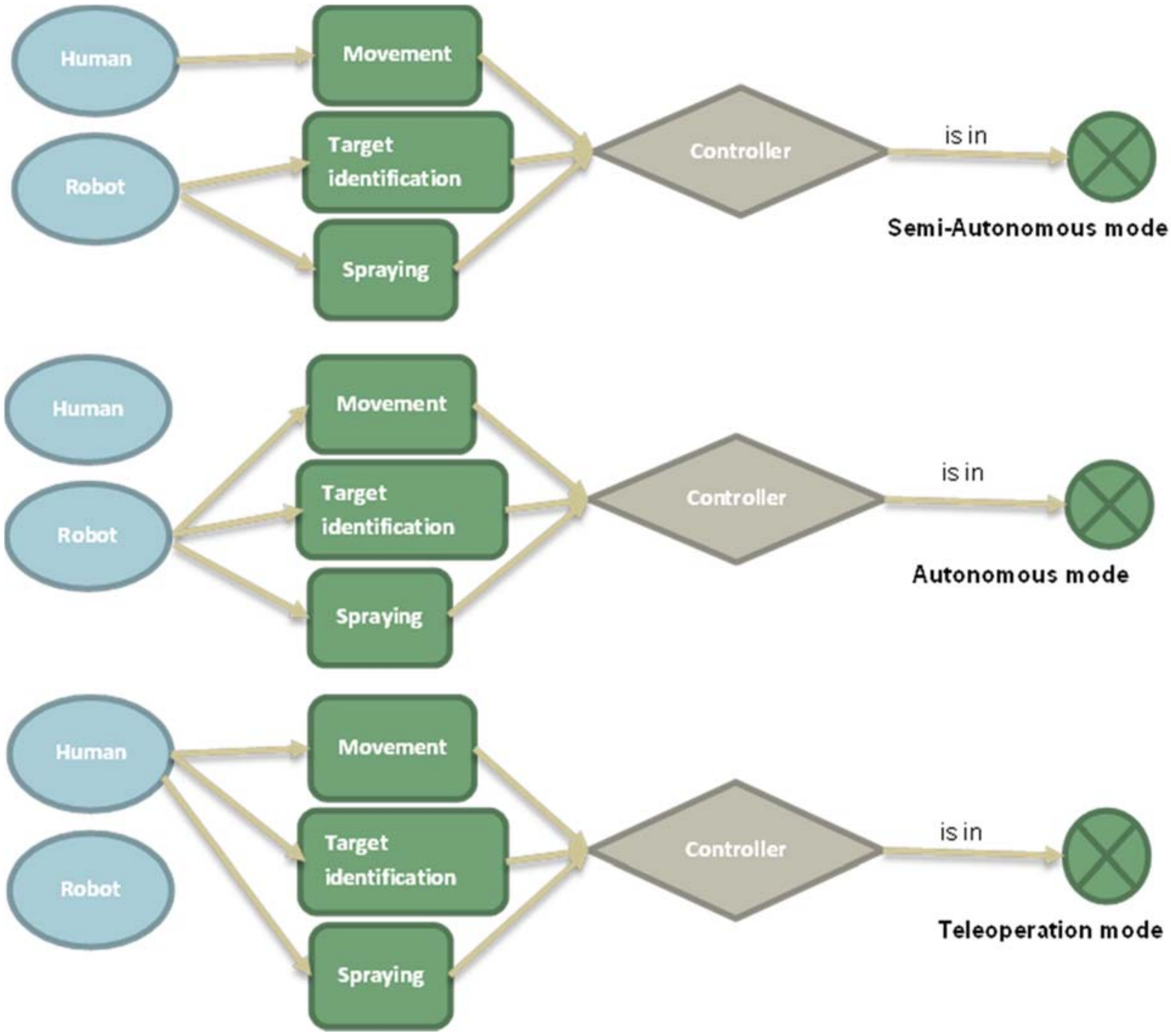



*Figure 14. UML State diagram: Mode of operation and levels of autonomy Illustration of levels of autonomy on agricultural robot sprayer*

The proposed framework for autonomy levels may seem rather straightforward and simple, however it actually brings forward important research questions, both theoretical (specific to HRI) and practical (specific to the user interface design). With respect to HRI the theoretical framework for semi-autonomous robot raises questions such as:

- Which operations can be pre-programmed and which can be manual?
- How does one divide the work between a robot and a human?
- What are the communication levels between robot and human?
- The human operator has the final call, but then what if the human is not available to give a response? What happens then?

With respect to the user interface, designers can use this framework to answer questions such as:

- What (robot) operations need to be included in the user interface?
- What triggers (on the user interface) a change between the autonomous mode, to semi-autonomous mode, to pure tele-operation?
- Issues of multimodal dialogue between human-robot (e.g. how is safety enhanced with audible and visible warnings?)
- How the human (operator) knows (at all times) in which mode the robot is operating?

In Table 3, examples of robot operation and the description of the two modes of each operation are presented.

*Table 3. Example of operations and their two modes*

| **Operation** | **Autonomous Mode** | **Teleoperation (manual) Mode** |
|---|---|---|
| Robot movement (Navigation) | The robot moves around the vineyard, stops, turns, speeds up or slows down according to pre-programmed instructions. | The operator online directs the movement of the robot through the interface. |
| Looking | The camera “looks” in a pre-programmed way. For example it can be fixed, or try to look ahead 25 cm, or swirl around 180o at a certain rate. | The operator points and the camera turns where the operator pointed. |
| Recognizing | A pattern recognition algorithm starts automatically (e.g. every 2 meters), recognizes a target and stores its position. | The operator uses interface controls to point to a target and the pointed position is stored. |
| Targeting | The robotic arm moves the sprayer nozzle towards the targets in a pre-programmed way, for example it targets the same place where a specific camera “looks” if the grape is ripe. | The operator directs the sprayer to target a specific position. |
| Spraying | Spraying is performed according to a pre-programmed algorithm taking into account timing, duration, intensity etc. | The operator specifies the characteristics of the spraying action and uses interface controls to start or stop the spraying. |

Regarding the framework presented, the AgriRobot has three operations: a) robot movement, b) target recognition, and c) spraying. The SAVSAR has an additional operation (using the robotic arm addition), that of target selection.

Let us consider a possible usage scenario of our SAARS to further illustrate how the semi-autonomous operation framework works. The spraying task has two modes: 1) autonomous, the spraying starts automatically for a predefined time, after the robot recognizes targets, and 2) manual, where the operator can start and stop the spraying manually. The recognition operation has also two modes: 1) autonomous, where the recognition operation is running in predefined intervals, and 2) manual, where the user starts the 'recognize' operation. If all operations are on autonomous mode then on the user interface the "Autonomous" mode is shown (see Figure 14). If all the operations are on manual mode then the "Teleoperation" mode is selected. If the operator intervenes in at least one operation, then the "Semi-Autonomous" mode is depicted on the user interface. In the case of target selection, let's assume that the robot is in autonomous mode (i.e. all operations are carried out as pre-programmed). After the target recognition algorithm completes, the operator may notice that some selections are wrong while others are missing. Intervening with user interface tools available (Figure 15) the operator can add / remove targets. In this case the mode of operation will change to semi-autonomous.


*Figure 15. Buttons for the target detection (series of look and recognize operations), target selection operation and spraying operation.*

### 4.4. The user interface

Figure 16 presents the final user interface of the SAARS system. This design of the user interface was based on recommendations from Adamides, et al. [2] related to the following factors: Platform Architecture and Scalability, Error Prevention and Recovery, Visual Design, Information Presentation, Robot State Awareness, Interaction Effectiveness and Efficiency, and Cognitive Factors. Furthermore, empirical findings from lab and field studies (see Chapter 4), were taken into consideration during the development of the user interface. In the following, the different components of the final version of the user interface are elaborated.


*Figure 16. The SAARS user interface - Top: Central camera view, Bottom: Peripheral camera view*

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 along 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.
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.

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 their main (full screen) view by using these on-screen buttons or by pressing the keys “p” or “o” on the keyboard.
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 (elaborated in the previous Section 3). 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 is carrying out 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.
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.
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 pushed, then the robot initiates the process and presents to the user interface (browser) 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.

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 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, labelled 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 arrows keys. The operator may control these two buttons from the keyboard as well by pressing the "q" and "w" keys, respectively.

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

### 4.5. Contribution

The main contribution of this chapter is the presentation of a methodology to transform a generic mobile robotic platform to an agricultural robot sprayer was presented, addressing both hardware and user interface design aspects and related problems faced and solutions provided. Additionally, a formal framework to specify the semi-autonomous mode of operation is proposed. Various user interfaces were designed and implemented to support semi-autonomous operation.

This methodology to transform the robotic platform to an agricultural robot sprayer was applied in the context of two research projects (AgriRobot and SAVSAR) and field-tested the result. The results of these experiments are presented in Chapter 6. The final version of the Open University of Cyprus AgriRobot, is shown in Figure 17.


*Figure 17. Left: The Summit XL mobile platform, Right: the transformed agricultural robot sprayer*

In addition, a formal framework of the levels of robot autonomy levels was presented. The rules that describe the transition between the levels of autonomy when the user intervenes in the robot operation are defined and illustrated with an implementation in the user interface of the developed systems.

Lab and field studies (to be presented in Chapter 4), provide evidence for the increased usability of the SAARv2 (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. However this small size might be suitable for greenhouse agricultural tasks.

An alternative solution (for open agricultural fields) 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).

Another solution to be taken into consideration would be to use multiple robots in the field.

# Chapter 5. A taxonomy of HRI usability heuristics

**Chapter overview**

Issues of usability, such as efficiency and effectiveness as well as user experience are involved in the teleoperated robot interface in ways similar to and different from human-computer interaction (HCI). Scholtz [150] argues that Human-Robot interaction is fundamentally different from HCI "*in several dimensions*". As she explains, these differences occur in the type of interaction roles, the physical environment where the robots operate, the physical and dynamic nature of the robots, the number of systems that an operator is interacting with, simultaneously, and finally the ability of the robots to perform autonomously.

Thus, the amount of research that exists in the field of HRI may not be known to new user interface designers. Therefore we need to codify this research, because without some type of taxonomy or guide, designers need to review a large amount of material, as well as distill what is helpful for their specific project.

This chapter presents a taxonomy of usability heuristics for robot teleoperation, developed from a focused literature review, collected robot teleoperation interface design guidelines, user-centered methods, and a five-year[7] design and field experience with a teleoperated agricultural robot.

## 5.1. Background information

Goodrich and Olsen [75] explain that, in robot teleoperation, there are two interaction loops between a human and a robot: (a) the remote human interacts with the robot via an interface, and (b) the robot interacts with the world via an autonomous mode. This interaction is restricted by the available technology and such limitations introduce workload bottlenecks or potential error conditions. They developed seven principles to counteract the effects of these bottlenecks, and to make interactions efficient: 1) implicitly switch interfaces and autonomy modes, 2) let the robot use natural human cues, 3) manipulate the world instead of the robot, 4) manipulate the relationship between the robot and the world, 5) let people manipulate presented information, 6) externalize memory, and 7) help people manage attention.

[7] http://www.savsar.gr and http://agrirobot.ouc.ac.cy funded research projects

Goodrich, et al. [74] introduced the ecological interface paradigm that combines video, map and robot pose information into a 3-D mixed reality display, which improves remote mobile robot teleoperation. This paradigm is based on Gibson's notion of affordances [69], which claims that "*...information to act appropriately is inherent in the environment*." Goodrich, et al. [74], explains that applying this theory to mobile robot teleoperation means that "*...an operator's decisions are made based on the operator's perception of the robot's affordances in the remote environment.*" Their ecological paradigm approach provides to the remote operator with appropriate information in a 3-D representation, such that the observed affordances of the remote robot match the actual affordances. This enables the operator to perceive, comprehend and project the state of the robot. Their results showed that a 3-D interface improved robot control, map building speed, robustness in the presence of delay, robustness to distracting sets of information, awareness of the camera orientation with respect to the robot, and the ability to perform search tasks while navigating the robot. Goodrich, et al. [74] conclude with three principles that led to the success of the 3-D interface: 1) present a common reference, 2) provide visual support for the correlation of action and response, and 3) allow an adjustable perspective. According to them, these principles "*...reduce the cognitive processing required to interpret the information from the robot and make decisions.*"

Clarkson and Arkin [42] assembled an initial list of HRI heuristics, modified it based on pilot studies, and validated it against existing HRI systems. Table 4 presents their proposed list of eight heuristics. Their work contributes a set of heuristics appropriate for use with HRI systems, derived from a variety of sources both in and out of the HRI field.

*Table 4. List of heuristics proposed in [42]*

| **HRI heuristics** |
|---|
| 1. Sufficient information design |
| 2. Visibility of system status |
| 3. Appropriate information presentation |
| 4. Use natural cues |
| 5. Synthesis of system and interface |
| 6. Error prevention |
| 7. Flexibility of interaction architecture |
| 8. Aesthetic and minimalist design |

Yanco, et al. [190] developed an initial set of guidelines for designing HRI in robots. Their study applied robotics, human-computer interaction, and computer-supported cooperative work (CSSW) expertise, to gain experience with HCI/CSSW evaluation techniques in the robotics domain. They analyzed four different robot systems that competed in the 2002 American Association for Artificial Intelligence (AAAI) Robot Rescue competition. Following this analysis, they developed guidelines for developing interfaces for HRI, presented in Table 5. Later, and based on these guidelines, Drury, et al. [49] applied the LASSO technique (Location Awareness, Activity Awareness, Status Awareness, Surroundings Awareness, and Overall mission Awareness), and evaluated HRI awareness in search and rescue robotics.

*Table 5. Preliminary set of guidelines designing HRI in robots from [190]*

| User interface design guidelines for HRI |
|---|
| 1. Provide a map where the robot has been |
| 2. Provided fused sensor information to lower the user's cognitive load |
| 3. Provide user interfaces that support multiple robots in a single display |
| 4. Minimize the use of multiple windows |
| 5. Provide more spatial information about the robot in the environment |
| 6. Provide robot help in deciding which level of autonomy is most useful |
| 7. Enhance awareness |
| 8. Lower cognitive load |
| 9. Increase efficiency |
| 10. Provide help in choosing robot modality |

Later, in 2007 and after three years of experience and observations of the competitors, in the AAAI Robot Rescue competition, Yanco and Drury [188] proposed a set of design guidelines that can be applied to urban search and rescue (USAR) situations for effective HRI. These included: 1) use a single monitor for the interface, 2) larger video windows assist in the success of the task, 3) window occlusion hinders operation, 4) when multiple robots are available, use one to view another, and 5) design for the intended user, not the developer. They believe that these guidelines should hold true for all tasks with remote teleoperated or semi-autonomous robots.

Scholtz, et al. [151], proposed six different issues in evaluation that must be considered to evaluate the overall human-intelligent system interaction, shown in Table 6. Later Scholtz, et al. [151] developed definitions of critical incidents and a coding scheme and used these to compare the performance of three teams in the USAR competition. Based on this assessment they examined the user interaction and identified potential information displays aiming to reduce the number of critical incidents. Based on this analysis they generated five guidelines for information display for USAR robots: 1) a frame of reference to determine position of robot relative to environment, 2) indicators of robot health/state, 3) information from multiple sensors presented in an integrated fashion , 4) the ability to self-inspect the robot body for damage or entangled obstacles, and 5) automatic presentation of contextually-appropriate information, such as automatically switching to a rear camera view if the robot is backing up.

*Table 6. Evaluation of interactions with human-intelligent systems presented by [149]*

| Issues for HRI evaluation |
|---|
| 1. Present the necessary information |
| 2. Present information in appropriate form |
| 3. Use efficient interaction language |
| 4. Effective and efficient interactions |
| 5. Interaction architecture scalability |
| 6. Support evolution of platforms |

Elara, et al. [54]delivered a list of modified heuristics (Table 7) for human-humanoid robot interaction based on Molich and Nielsen [119] original list of usability heuristics.

*Table 7. Elara, et al. [54] list of modified heuristics*

| List of heuristics |
|---|
| 1. Visibility of system status |
| 2. Clarity in information presentation |
| 3. Match between system and the real world |
| 4. Prioritize placement of information |
| 5. Extensibility of the system |
| 6. Help users recognize, diagnose and recover from errors |
| 7. Effective communication architecture |
| 8. Aesthetic and minimalist design |

Keyes, et al. [104] presented lessons learned from the evolution of human-robot interaction design for improved awareness in USAR remote robot operations, including new design guidelines. They argue that awareness is the most important factor in completing a remote robot task effectively. As a results from their study they composed a list of guidelines recommended by Yanco, et al. [190] and Scholtz, et al. [151], as well as they adapted heuristics from Nielsen [126]. Additionally, the included items to support the operator's awareness of the robot in five dimensions, as shown in Table 8.

*Table 8. Guidelines to support the operator's awareness from [104]*

| | Guidelines to support the operator's awareness |
|---|---|
| 1. | Enable an understanding of the robot's location in the environment |
| 2. | Facilitate the operator's knowledge of the robot's activities |
| 3. | Provide to the operator an understanding of the robot\s immediate surroundings |
| 4. | Enable the operator to understand the robot's status |
| 5. | Facilitate an understanding of the overall mission and the moment-by-moment progress towards completing the mission |

Finally, Labonte, et al. [107] explain that navigation and environmental challenges that a teleoperated robot faces, requires an appropriate teleoperation interface for safe and efficient usage by novice users. In their paper, they describe the design criteria and characterize visualization and control modalities of user interfaces with a real robot. They take into consideration the user's needs along with the current state-of-the-art in teleoperation interfaces. They compared two novel mixed reality visualization modalities with standard video-centric perspectives. Based on their results they concluded that mixed reality visualization modalities significantly improve the performance of novice users. The user interface guidelines for teleoperation interfaces proposed by Labonte, et al. [107] are included in Table 9.

*Table 9. Labonte, et al. [107]composition of user interface guidelines*

| | User interface guidelines |
|---|---|
| 1. | Provide a frame of reference to determine the robot's position in the environment Facilitate the operator's knowledge of the robot's activities |
| 2. | Memorize in a map where the robot has been |
| 3. | Ability to self-inspect the robot's body for damages or entangled obstacles |
| 4. | Information from multiple sensors presented in an integrated fashion |
| 5. | Complement video stream with feedback information from other sensors |
| 6. | Minimize the use of multiple windows |
| 7. | Automatic presentation of contextually-appropriate information, such as automatically switching to a rear camera view if the robot is backing up |
| 8. | Allow the user to adjust the perspective of the environment to match the task |
| 9. | Ground the information displayed with the reality |
| 10. | Provide indicators of robot health/state (e.g. camera being used, position(s) of camera(s)) |

11. Display the robot's body in the interface
12. Convey the information of the video stream with respect to robot orientation
13. Easy transition to more in-depth information
14. User control and freedom
15. Implicitly switch interfaces modality and autonomy
16. Allow the user to manipulate the information displayed and to store information
17. Help direct the operator's focus of attention
18. Provide assistance and autonomous modes
19. Useful and relevant information
20. Let the robot use natural human cues
21. Manipulate relationship between robot and world
22. Learning mechanisms

Based on the above literature review, it is obvious that several sets have similar or complementary guidelines that can be grouped into more general categories; these groupings may differ depending on one's mental model. However, identification of a set to be used for a usability inspection is not obvious. To codify these fragmented guidelines for the design and development of HRI interfaces, HCI and HRI practitioners were involved in the various phases of developing the proposed taxonomy. The card sorting method was used.

## 5.2. Development of the taxonomy: The procedure

### *5.2.1 Open card sorting*

First, an open card sorting exercise was used for an initial categorization of the 70 identified guidelines. According to Spencer [162] and Tullis and Wood [170], the goal of open card sorting is to generate a user-centered taxonomy. Open card sorting can be particularly helpful in situations in which one needs to come up with a new organizational scheme and also it helps to learn how people (in our case HRI/HCI and usability experts) think about groupings in content. Spencer [161] also explains that open card sorting is a quick, inexpensive and reliable method to generate an overall structure of the information and possible taxonomies.

*1) Participants:* Six female and 16 male experts (a sufficient number for card sorting exercises [162]) participated in the open card sorting study. Emails and LinkedIn groups related to HRI, HCI, Information Architecture, and Usability, such as ACM SIGCHI, ICT-AGRI ERA-NET, User Experience Group, Usability Experts, Human Robot

Interaction, HCI Researchers, and Information Architect were used for recruitment. An announcement was posted in Facebook pages related to HRI and HCI.

*2) Apparatus:* The open card sorting was conducted over two months using the WebSort online service (Figure 18). WebSort enables researchers to perform remote card-sort studies. After entering the 70 user interface guidelines into the WebSort tool, a study was created. An announcement of the study was prepared which included the web link to the study, the instructions for its completion, and a brief explanation of the study objective and rationale.

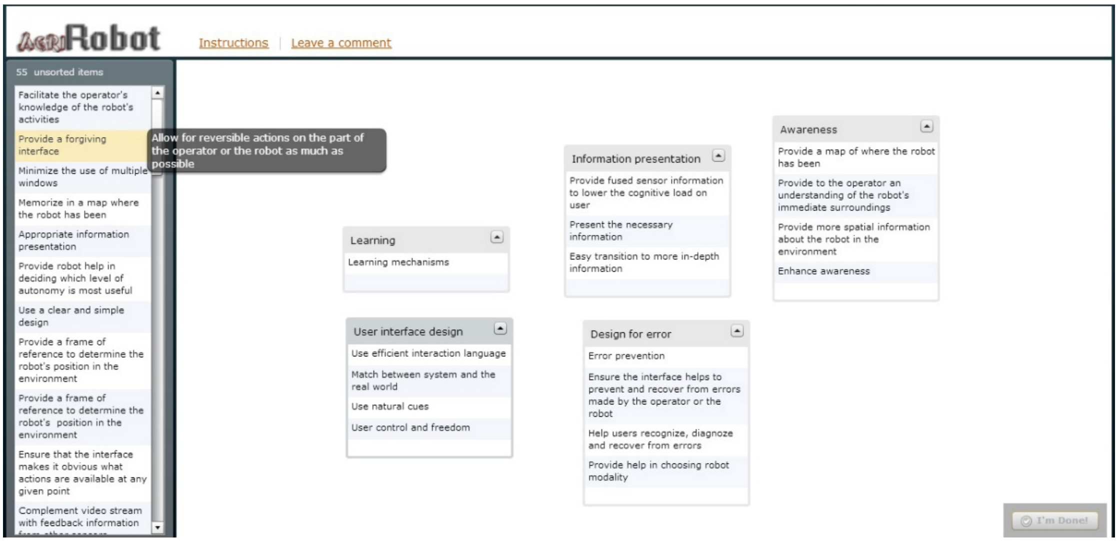



*Figure 18. WebSort participant's user interface screenshot*

*3) Procedure:* The participants were presented with instructions on the study and WebSort usage and the 70 guidelines through the WebSort tool in randomize order. Each participant could drag and drop cards in order to form groups and was prompted to produce names for these groups. Participants produced on average 8.5 categories (SD=3.6), placed an average of 8.5 items in each category (SD=6.2) and completed their sorting in approximately 46 minutes.

### *5.2.2 Closed card sorting*

The closed card sorting survey aimed to validate and refine the taxonomy derived by analyzing the open card sorting data.

*1) Participants:* Twenty female and 18 male experts, with an average age of 41, participated in the closed card sorting study. Twenty-three were HCI and 15 were HRI practitioners. They were recruited through open invitations in social media networks (LinkedIn, ResearchGate, and Facebook) and direct email contacts. In addition to the target group for the open card sort, a question was posted in ResearchGate and was tagged with research topics such as human-robot interaction, taxonomy, HCI, and field robot teleoperation. According to the log files from OptimalSort, 28 of the participants were recruited from LinkedIn posts, 6 from email contacts, 2 from Facebook, and 2 from ResearchGate.

*2) Apparatus:* The closed card sorting exercise was conducted using the OptimalSort online service with the 70 guidelines and the eight predefined categories. After entering the 70 user interface guidelines into the OptimalSort system along with the eight predefined categories, the survey was created. An announcement of the survey was authored which included the web link to the study, the instructions for its completion, and a brief explanation of the study objective and rationale. The online survey was available for two weeks. Figure 19 presents the OptimalSort interface used by the participants in our closed card sorting survey. Both the list of guidelines and the available categories were presented in a random order to the participants.

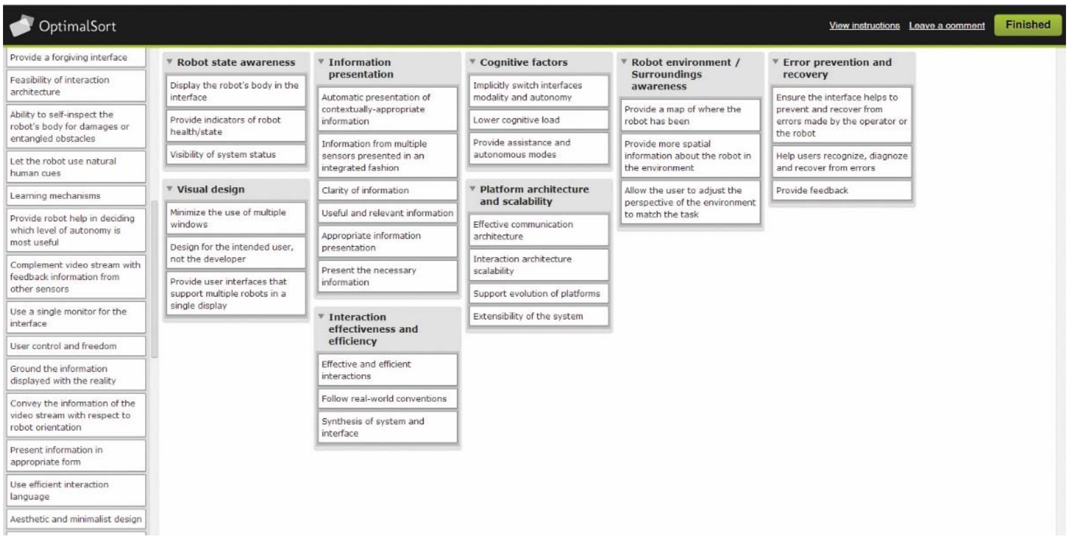



*Figure 19. OptimalSort participants user interface screenshot*

*3) Procedure:* Both the list of guidelines and the available categories were presented in a random order. Each participant could drag and drop cards into the eight predefined categories. On average it took them 17 minutes to complete the task.

## 5.3. Proposed taxonomy

### *5.3.1 Taxonomy generation: Analysis of the open card sorting*

Websort delivers the categorizations provided individually and cumulatively by participants, with the number of times each guideline was placed in each category. It also provides a tree graph, the “dendrogram,” that visually presents the results of an average-linkage hierarchical cluster analysis [184]. The dendrogram’s lines are calculated as follows: one calculates the number of times two items were placed in the same category (regardless of that category's name), and the more often they were put together the shorter the lines that connect the two items. The longer the line, the less conceptually related those two items, or groups of items are. This dendrogram is shown in Figure 20 with a specified number of eight color-coded top level groups.

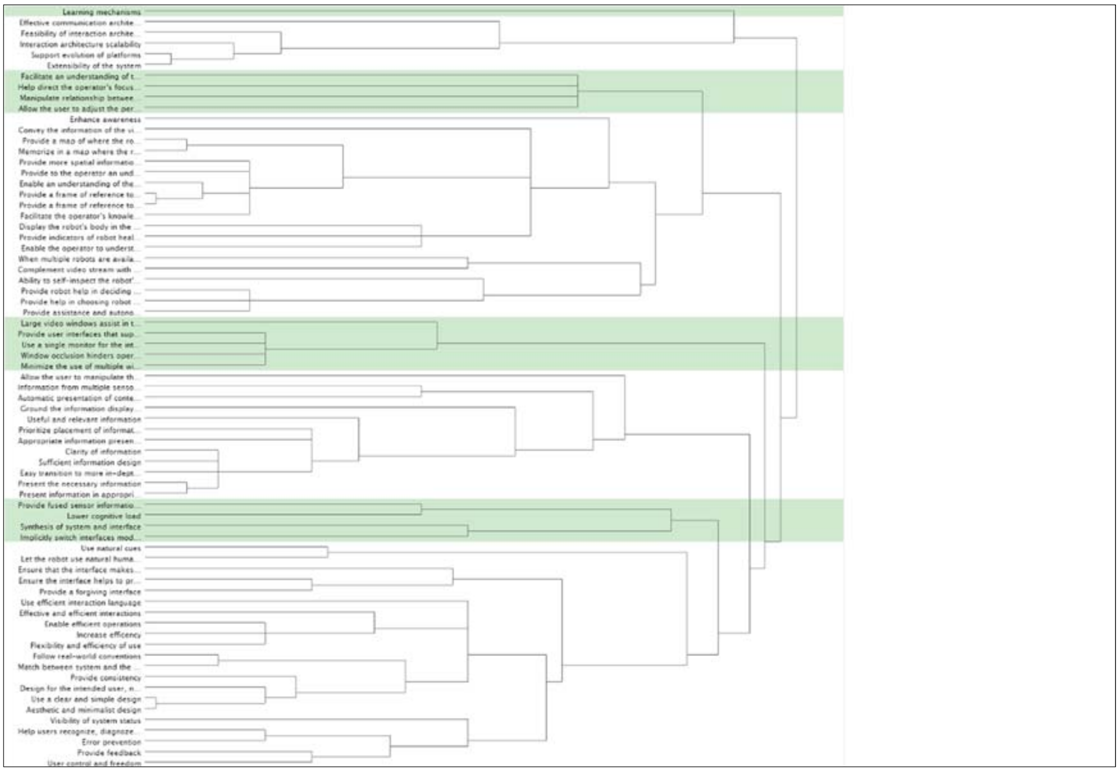


*Figure 20. Tree graph (dendrogram) with eight color-coded top level groups*

In an attempt to limit any singly person biases, three experts were involved in the analysis of the open card sorting data and created their own categorizations, according to different methods. One expert used common nominalizations in the participants' groupings to merge the categories. For example, names such as "Look," "Orientation," "Robot help for navigating and task pursuit," "Video," and "Video stream" were grouped into the single category "Viewing and navigation." This resulted into six meta-categories. Consider a meta-category A, proposed by the expert, that includes categories 1, 2, and 3 proposed by the participants of the open card sorting. For each guideline, a sum indicated how many times the guideline was found in categories 1, 2, and 3. If this sum was the maximum from all the meta-category sums, then the guideline was assigned to meta-category A. This whole process took about seven hours.

Another expert used the dendrogram (Figure 20) produced by WebSort with the groupings from the 22 participants. The groupings were based on the average-linkage hierarchical cluster analysis algorithm [96, 184]. An in-depth exploration of WebSort's tree graph resulted in the identification of groups that were formed by participants and included the same guidelines. Group labels were created taking into consideration standardized tags from the literature. For instance, the guidelines "Help users recognize, diagnose and recover from errors," "Error prevention," and "Provide feedback" were placed in the group with a standardized label "Design for error prevention and recovery." The process required approximately three and a half hours to complete.

A third expert analyzed the card sorting data following the steps described in [162]. First, linguistically or conceptually similar group labels were transformed into a single standardized group label using WebSort's merging functionality. For instance, participants' group labels "Design efficiency," "Efficiency," "Efficiency of the interface," "Efficient experience," "Interaction efficiency," and "Usage efficiency" were standardized into "User experience efficiency." Next, an in-depth exploration of a matrix with guidelines as rows, standardized group labels as columns, and each cell representing the percentage of participants that placed each guideline in each standardized group was conducted. Column-wise exploration of this matrix combined with inspection of WebSort's dendrogram resulted in the identification of groups consistently formed by participants and including the same guidelines. For instance, the guidelines "Feasibility of interaction architecture," "Support evolution of platforms," "Extensibility of the system," and "Effective communication architecture" were consistently placed in the group with the standardized label "Platform architecture and scalability." Next, row wise exploration of this matrix was used to place guidelines in the identified groups. Guidelines that were placed in two groups by a roughly equal percentage of participants were placed in both categories in the expert's proposed categorizations. Such a case was the guideline "Facilitate the operator's knowledge of the robot's activities," which grouped under the "Robot environment/ surroundings awareness" and "Robot state awareness" categories. The whole process required approximately seven hours.

The three experts iteratively reviewed the guidelines within each category, as well as moved, removed, or merged guidelines from their initial position in the three taxonomies initially proposed. This resulted in a new eight-category taxonomy expressing their consensus, including category headings.

### *5.3.2 Taxonomy validation: Analysis of the closed card sorting*

A high overall agreement (86%) between closed the open card sorting was observed (detailed results in Appendix III). For each guideline, the percentage of closed card sorting participants who placed it in a category different from the one it was placed in the open card sorting study was compared to the percentage of closed card sorting participants who placed it in the same. For only 10 out of 70 guidelines, a statistically significant difference was found, using a two-sided two-proportion z-test and the standard value of $p<0.05$ to decide statistical significance. The proposed taxonomy was refined by moving these ten items in the category selected by the majority of the closed card sorting participants.

## 5.4. The final taxonomy

Table 10 presents the final taxonomy and a description for each category follows next.

*Table 10. Taxonomy of Usability Heuristics*

| | |
|---|---|
| **1** | **Platform Architecture and Scalability (5)** |
| | • Extensibility of the system<br>• Support the evolution of platforms<br>• Interaction architecture scalability<br>• Effective communication architecture<br>• Flexibility of interaction architecture |
| **2** | **Error Prevention and Recovery (5)** |
| | • Error prevention<br>• Ensure the interface helps to prevent and recover from errors made by the operator or the robot<br>• Help users recognize, diagnose and recover from errors<br>• Provide a forgiving interface, allowing for reversible actions on the part of the operator or the robot as much as possible<br>• Provide feedback |
| **3** | **Visual Design (10)** |
| | • Aesthetic and minimalist design<br>• Use a clear and simple design<br>• Large video windows assist in the success of the task<br>• Minimize the use of multiple windows<br>• Display the robot's body in the interface<br>• Provide UI that support multiple robots in a single display<br>• Design for the intended user, not the developer |

| | |
|---|---|
| | • Use a single monitor for the interface<br>• Window occlusion hinders operation<br>• Provide consistency; especially consistency between robot behavior and what the operator has been led to believe based on the interface |
| **4** | **Information Presentation (12)** |
| | • Appropriate information presentation<br>• Clarity of information<br>• Useful and relevant information<br>• Present information in appropriate format<br>• Present the necessary information<br>• Prioritize placement of information<br>• Sufficient information design<br>• Information from multiple sensors presented in an integrated fashion<br>• Automatic presentation of contextually-appropriate information<br>• Easy transition to more in-depth information<br>• Allow the user to manipulate the information displayed and to store information<br>• Ground the information displayed with the reality |
| **5** | **Robot State Awareness (10)** |
| | • Provide indicators of robot health/state (e.g. camera being used, position(s) of camera(s))<br>• Enable the operator to understand the robot's status<br>• Provide robot help in deciding which level of autonomy is most useful<br>• Facilitate the operator's knowledge of the robot's activities<br>• Ability to self-inspect the robot's body for damages or entangled obstacles<br>• Provide help in choosing robot modality<br>• Visibility of systems status<br>• When multiple robots are available, use one to view another<br>• Facilitate an understanding of the overall mission and the moment-by-moment progress towards completing the mission<br>• Complement video stream with feedback information from other sensors |
| **6** | **Interaction Effectiveness and Efficiency (12)** |
| | • Effective and efficient interactions<br>• Flexibility and efficiency of use<br>• Increase efficiency<br>• Use efficient interaction language<br>• User control and freedom<br>• Enable efficient operation<br>• Implicitly switch interfaces modality and autonomy<br>• Ensure that the interface makes it obvious what actions are available at any given point |

| | |
|---|---|
| | • Use natural cues<br>• Synthesis of system and interface<br>• Match between system and the real world<br>• Let the robot use natural human cues |
| **7** | **Robot Environment/Surroundings Awareness (10)** |
| | • Enable an understanding of the robot's location in the environment<br>• Provide to the operator an understanding of the robot's immediate surroundings<br>• Provide more spatial information about the robot in the environment<br>• Provide a frame of reference to determine the robot's position in the environment<br>• Memorize in a map where the robot has been<br>• Provide a map of where the robot has been<br>• Manipulate relationship between robot and world<br>• Convey the information of the video stream with respect to robot orientation<br>• Allow the user to adjust the perspective of the environment to match the task<br>• Enhance awareness |
| **8** | **Cognitive Factors (6)** |
| | • Lower cognitive load<br>• Provide fused sensor information to lower the cognitive load on user<br>• Learning mechanisms<br>• Follow real-world conventions<br>• Help direct the operator's focus of attention<br>• Provide assistance and autonomous modes |

1) **Platform architecture and scalability**: "Provide the flexibility to iterate robotic and computing technological developments in the user interface of the HRI system." The user interface of an HRI system should be flexible to follow and benefit from developments in computing and robotic technologies.

2) **Error prevention and recovery**: "Provide information and alerts to avoid and recover from user errors." The information provided by the user interface should prevent user errors, and if a user makes a mistake, the user interface should allow for its rectification. In contrast with undoing a "Cut" operation in a word processor, a "Cut" command to prune a tree through a teleoperated AgriRobot cannot be undone.

3) **Visual design**: "Provide an aesthetic, clear, and simple design of the user interface with the relevant information necessary." Since the user interface is the communication medium between the operator and the remote robot, it should provide the operator only relevant information (from video and other robot sensors) in a simple, consistent, effective, and minimalist way. Specific examples include minimizing use of

multiple windows, avoiding window occlusion, providing large video windows and displaying the robot's body in the interface.

4) **Information presentation**: "Provide the necessary information, in the right context, moment, and modality." Controlling a remotely located robot is demanding on operators who need to integrate various sources of information coming from the robot cameras and sensors. Therefore, information presentation is of high importance in this type of user interface designs, to enhance situation awareness of the operators, and to bridge the gaps of execution and evaluation [25].

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." The robot should be able to self-inspect its systems and take autonomous action or ask for user intervention. The human operator should have a clear understanding about the robot's status and its activities. For instance, to support understanding of the camera(s) and their position(s), the overall mission and the current progress, and when multiple robots are available, use one to view another.

6) **Interaction effectiveness and efficiency**: "Provide efficient and effective interactions between human and robot." In HRI, efficiency is measured in terms of the time required to complete a task; effectiveness is measured in terms of how well a task is completed.

7) **Robot environment/surroundings awareness**: "Provide spatial information about the robot's surroundings and the environment where it is operating." Environment awareness is essential, because in field robot teleoperation it is important to have knowledge of the robot's whereabouts and the area covered, such as orientation, obstacles, or why a robot is not moving. This can be accomplished through maps, orientation information (such as compass), and sensors that will provide the necessary information about the robot's surroundings.

8) **Cognitive factors**: "Use mental models and metaphors to lower the cognitive load." Cognitive factors are characteristics that affect performance and learning. The user interface of a teleoperated HRI system should be designed such that it directs the user's attention to the task the robot is operating, improves learnability, and provides fused information from the various sensors and cameras from the robot, in order to lower the cognitive load on the user.

These categories are not displayed in any particular order, and none takes precedence over another. They are all equally weighted in the design and evaluation of any HRI. Thus, when using these categories of guidelines to design an HRI for teleoperation, it is suggested that all of them are considered. It is underlined that the guidelines can be used to help during both interface design and evaluation. Such an application of the proposed taxonomy in the context of the heuristic evaluation of a teleoperated agricultural robot sprayer is presented in the next chapter.

### 5.5. Contribution

This chapter presented a systematic user-centered approach to the creation of a taxonomy of usability heuristics for robot teleoperation. The approach started with an initial extensive literature review in the area of teleoperated robotics and the assembly of a list of guidelines based on the reviewed literature. This was followed by an open-card sorting exercise for their classification, a focus group exercise for the creation of the proposed taxonomy of guidelines based on the collected open-card sorting data analysis. Finally, a closed card sorting exercise was carried out to validate and further refine the proposed taxonomy. As a result, the initial set of 70 guidelines / heuristics was grouped into eight distinct categories (the taxonomy): Platform Architecture and Scalability, Error Prevention and Recovery, Visual Design, Information Presentation, Robot State Awareness, Interaction Effectiveness and Efficiency, robot surroundings/ environment awareness, and Cognitive Factors.

The main contribution of this chapter is the development of a taxonomy of usability heuristics for robot teleoperation, following an approach that involved the end-users of such heuristics (i.e., HRI/HCI practitioners). Such a taxonomy should be valuable especially in the design and evaluation of usable teleoperated mobile robots in the field. The novelty of the presented taxonomy, compared to reviews (e.g.[118]) and taxonomies (e.g. [189]), is that it focuses specifically on the user interface design of HRI systems for teleoperated mobile field robots.

The taxonomy is supported by a body of literature, and the process followed has been used successfully in other taxonomy studies, such as grouping research-based web design and usability guidelines [9], producing a taxonomy of web design guidelines for older people [10], grouping guidelines for describing usability problems [11], and developing a taxonomy linking game attributes to learning [12]. The process has exposed the guidelines to several HCI/HRI experts, thus providing confidence towards its use by any prospective users.

This study captures existing HRI guidelines and provides a synopsis of existing knowledge about the design and evaluation of teleoperated robotic interfaces. The guidelines have been used during the design phase of the development of user interfaces for HRI in vineyard spraying and have proved useful for heuristic evaluation in identifying usability issues for the teleoperated vineyard robotic sprayer.

# Chapter 6. HRI Usability Evaluation: Field and Laboratory Experiments

**Chapter overview**

This chapter presents findings related to the human factors and ergonomics, following an investigation of the usability of different interaction modes, for agricultural robot teleoperation. In addition, it presents findings from a heuristic evaluation of three versions of the user interface that were iteratively designed, following the field experiment and based on the experiences gained from using the robot in the field and in the laboratory.

## 6.1. HRI usability evaluation: Lab and Field experiments

In this section findings from four HRI usability evaluations are presented. The first experiment one was carried out in a lab and evaluated pointing devices using a robot simulation in a vineyard (section 6.2). The second experiment took place in a vineyard field and evaluated the usability of different interaction modes of a teleoperated agricultural robot sprayer (AgriRobot). The third experiment took place in the lab where three versions of a human-robot interface for a semi-autonomous agricultural vineyard robot sprayer were evaluated using the heuristic usability evaluation method. The last experiment (SAVSAR project) took place in the field with the goal to evaluate the user experience of the final version of the user interface (section 6.5).

## 6.2. User testing in the lab investigating effect of target selection input device

The main goal of this study (Appendix I) was the empirical evaluation of the following design factor: 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. All participants were asked to interact with the prototype in the three following settings which were selected in random order: 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 Figure 21).

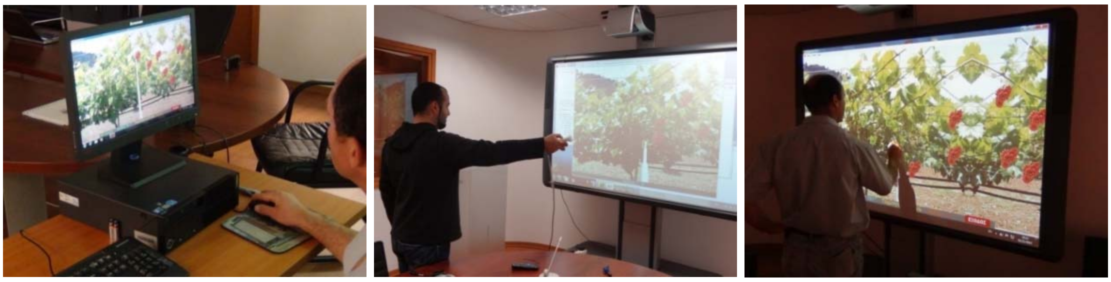


*Figure 21. Selecting targets (grape clusters) using a mouse (left), a Wiimote (middle), and a digital pen on a smart interactive whiteboard (right)*

Fifty participants were involved in the experiment, 25 practitioners (farmers and agronomists), 19 male, 6 female, with average age 41 (sd=9.9), and 25 university students majoring in computer science, 10 male, 15 female, with average age 22 (sd=1.5). 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 log files analysis reveals that participants were most efficient and effective when using the digital pen as compared to the mouse and the Wiimote. Results are shown in Table 11. Participants' effectiveness was measured by the mean percentage of the grape clusters that were successfully sprayed against the total number of grapes; again the digital pen and the mouse were more effective as compared to the Wiimote. Based on follow-up interviews, the participants' replies confirmed that their preference to the mouse was their familiarity when using it for desktop applications, whereas their positive attitude towards the digital pen was its ease of use. They also expressed their difficulty to control the pointing action when using the Wiimote controller and attributed that to their unfamiliarity with the device.

*Table 11. Summary of the log files analysis*

| **Total number of grapes** | **Mouse** | **Wiimote** | **Digital Pen** |
|---|---|---|---|
| Mean | 357.16 | 273.62 | 386.34 |
| Minimum | 239 | 188 | 245 |
| Maximum | 525 | 410 | 544 |
| **Number of grapes sprayed** | **Mouse** | **Wiimote** | **Digital Pen** |

| | | | |
|---|---|---|---|
| Mean | 326.92 | 163.50 | 359.90 |
| Minimum | 41 | 61 | 152 |
| Maximum | 449 | 296 | 524 |

### 6.3. Field experiment: HRI usability evaluation of different interaction modes

The following work is related with the evaluation of user interfaces for human-agricultural robot interaction; it is related to agricultural robotics and related agricultural tasks. As such, the interest is concentrated on the farmer-user of the system. Specifically, this section investigates the usability of different interaction modes for agricultural robot sprayer teleoperation in a vineyard field. Two different types of peripheral vision support mechanisms, two different types of control input devices, two different types of output devices and the overall influence of user interface on observed and perceived usability were examined. Two different tasks were performed: (a) robot path guidance (navigation) along vineyard rows while avoiding obstacles, and (b) targeting spray clusters.

***The task***

The operator was situated remotely from the field while the robot was operated in the vineyard which was 150 meters away. Participants were asked to guide the robot along vineyard rows, avoiding obstacles, and to identify and spray grape clusters. They were asked to guide the robot, using the PS3 gamepad or the PC keyboard, for 50 meters in a vineyard row, then make a turn 180 degrees followed by navigating another 50 meters in the next vineyard row. There were signs in the field to inform participants where to make a turn and when to stop. Each participant used all the eight user interfaces in random order. Video feedback from the robot's cameras and sensor information were displayed in the user interface. The operator could view the robot cameras either from a 17 inch PC screen or via a video eyewear (head mounted display) based on Vuzix Wrap 920AR, which also included a Wrap Tracker 6TC; a motion tracker that plugs into a special port on the Wrap 920 enabled software to monitor the operator's direction and angle of view as well as movement. During the task, the participants' interaction with the system was monitored by the experimenter who was taking notes and recording the entire experiment. The following metrics of the human-robot collaboration effectiveness and efficiency (performance measures) were collected per user interface used: a) total number of sprayed vines, b) total number of collisions with obstacles, and c) overall time required completing the task.

***Participants***

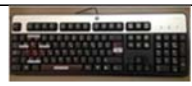
Thirty participants were involved in the study (7 females, 23 males), aged 28-65 (M=39.8, SD=9.3). Sixteen participants were farm workers, and 14 were scientists with agricultural background (agronomists). Educational levels were as follows: eight participants had completed secondary school, fifteen had completed university education, three had a postgraduate degree and four had a PhD.

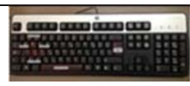
***AgriRobot sprayer and user interfaces***

The agricultural robot sprayer that was used in the experiment is based on the Summit XL mobile platform by Robotnik and was presented earlier in detail in Chapter 2. This AgriRobot was adapted for teleoperation for both navigation and spraying tasks using the PS3 gamepad or a PC keyboard (keys used were W:forward, S:backward, A: turn left, D: turn right, and Spacebar for spraying on/off).

Eight alternative user interfaces configurations were developed reflecting the combination of all the aforementioned factors' levels examined in this study (Table 12).

*Table 12. The experiments' conditions and respective user interfaces for robot teleoperation*

| **User interface** | **Factor 1: type of screen output** (PC Screen vs HMD) | **Factor 2: number of views** (Single View vs Multiple Views) | **Factor 3: type of robot control inputs** (PC Keyboard vs PS3 gamepad) |
|---|---|---|---|
| User interface 1<br>PC screen + single view + PS3 |  |  |  |
| User interface 2<br>PC screen + multiple views + PS3 |  |  |  |
| User interface 3<br>PC screen + single view + keyboard |  |  |  |
| User interface 4 |  |  |  |

| | | | |
|---|---|---|---|
| PC screen + multiple views + keyboard | | | |
| User interface 5<br>HMD + single view + PS3 |  |  |  |
| User interface 6<br>HMD + multiple views + PS3 |  |  |  |
| User interface 7<br>HMD + single view + keyboard |  |  |  |
| User interface 8<br>HMD + multiple views + keyboard |  |  |  |

***Questionnaires***

Study questionnaires were administered in the participants' native language (English or Greek). We provided this option in an attempt to minimize potential threats to the validity and reliability of questionnaire data obtained from non-native English speakers [64]. The Greek version of SUS [103, 134] was used. Likewise, the Greek version of GSE was used [71], whereas the rest questionnaires were translated by the authors and pilot-tested before the experiment.

***Pre-experiment questionnaires***

*Immersive Tendency Questionnaire (ITQ).* This questionnaire measures the differences in the tendencies of individuals to experience presence. The original version of the ITQ was developed by Witmer and Singer [183], with a Cronbach's Alpha of 0.78. The ITQ used in this experiment, was a revised version that consisted of 18 questions. This was because auditory and haptic items were not used during the experiment, given that these were not available in the developed system. The scoring takes into consideration four main groups: Focus – tendency to maintain focus on current activities (questions 1, 2, 3, 8, and 13), Involvement – tendency to become engaged in activities (questions 4, 5, 10, 12, and 18), Emotions – Tendency to become involved in activities (questions 11, 15, 16, and 17), and Games – tendency to play video games (questions 6, 9, and 14).

*General Self Efficacy scale (GSE).* The GSE developed by Schwarzer and Jerusalem [153] is used to assess respondents' general sense of perceived self-efficacy. GSE predicts how well one is coping with daily hassles as well as how well one adapts after experiencing stress. The responses to the GSE scale in each of the ten questions are provided on a 4-point scale and then summed up to yield the final composite score with a range of 10 to 40. According to Jerusalem et al. (1992), perceived self-efficacy reflects an optimistic self-belief that one can perform a novel or difficult task or cope with adversity. According to Schwarzer and Jerusalem [153], based on samples from 23 nations, the Cronbach's Alpha ranged from 0.76 to 0.90, with the majority in the high 0.80s.

*Santa Barbara Sense of Direction scale (SBSOD).* The SBSOD scale [85] was introduced in 2002 as a self-reported measure of environmental spatial ability. The recommended scoring procedure for the scale is to first reverse score for the positively phrased items, then sum the scores for all of the items together, and then divide the total by the number of items. The SBSOD score is a number between 1 and 7; the higher the score, the better the perceived sense of direction.

***Post-task questionnaires***

*System Usability Scale (SUS).* The SUS [35] is a technology independent and reliable tool for measuring perceptions of usability. Bangor, et al. [15] analyzed a SUS dataset of 2300 individual surveys collected from more than 200 studies and found a Cronbach's Alpha of 0.91. The SUS consists of a 10 item questionnaire with five response options for respondents; from 'strongly agree' to 'strongly disagree'. Five of the items are positively phrased, whereas the rest five are negatively phrased. The SUS scale score ranges from 0 to 100, where the higher the score, the better the perceived usability of the system.

*Presence Questionnaire (PQ).* The PQ measures the degree to which an individual experiences presence in a virtual environment and the influence of possible contributing factors on the intensity of this experience: Control Factors, Sensory Factors, Distraction Factors, and Realism Factors, described in detail in Witmer and Singer [183]. Internal consistency measures of reliability (Cronbach's Alpha) for the PQ yielded reliability of 0.88 [183].

*NASA Task Load Index (NASA-TLX) questionnaire.* The NASA-TLX is an instrument that allows users to perform subjective workload assessments on operators' working with various human-machine systems [84]. NASA-TLX is a multi-dimensional rating procedure that derives an overall workload score based on a weighted average of ratings on six subscales: Mental Demands, Physical Demands, Temporal Demands, Own Performance, Effort and Frustration. The NASA-TLX has been in use for more than 20 years [83, 84]. It was translated into more than a dozen languages and is administered verbally, in writing or by computer. It has been subjected to a number of independent evaluations in which its reliability, sensitivity and utility were assessed and compared to other methods of measuring workload. In this study the NASA-TLX was administered on a computer [174].

***Experimental procedure***

First, participants signed a consent form. Next, they answered a pre-experiment questionnaire that included demographics related questions, the ITQ scale, the GSE scale and the SBSOD scale. Next, the task was explained to the participants and they were allowed to get familiarized with the user interface for five minutes. Following the interaction with each user interface, the participant was asked to answer the following: the SUS questionnaire [35], the presence questionnaire [183], and the NASA TLX [84]. In order to avoid fatigue effect, each participant used half of the user interfaces in one day and the remaining four user interfaces one week later. The experimental procedure was approved by the university ethical committee.

***Statistical analyses***

Statistical analyses of the collected data were conducted in order to compare the three factors. In all statistical analyses, the assumption of normality was investigated using the Shapiro-Wilk test. The d family of effect size was used to measure the magnitude of difference in standard deviation units. According to Leech, et al. [109], an effect size d of .5 means that the groups differ by one half of the pooled standard deviation and that usually d effect sizes vary from 0 to ± 1, but can also be more than 1, though it is relatively uncommon.

To examine the effect of the three interaction factors (type of screen output, number of views and type of robot control input device), on actual usability, efficiency (time in inverse scale) and effectiveness (number of grapes sprayed), 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.

To examine the effects of the three interaction factors, in addition to the participants' sense of direction (SBSOD) on the AgriRobot system's actual usability, efficiency (time in inverse scale) and effectiveness (number of grapes sprayed), and perceived usability (SUS score), the LMM and a logistic regression in the framework of the GLMM were used. In both cases the fixed effects were the three interaction factors (including their second and third order interactions) and the SBSOD score (as a covariate) and the participants were included as a random effect to account for individual differences among them.

To examine the effects of the three interaction factors in addition to the participants' general sense of perceived self-efficacy on the perceived work load, the LMM was used. The fixed effects were the three interaction factors (including the second the third interactions) and the GSE score (as a covariate) and the participants were included as a random effect to account for individual differences. The dependent variable in this analysis was the NASA-TLX total score. In this analysis, eta squared ($\eta^2$) which belongs to the r family of effect sizes, were reported.

Finally, to examine the effects of the three interaction factors in addition to the participants' immersion tendency (ITQ) on the AgriRobot system's actual usability, efficiency (time in inverse scale) and effectiveness (number of grapes sprayed), the LMM was used. The fixed effects were the three interaction factors (including the second the third interactions) and the ITQ score (as a covariate) and the participants were included as a random effect to account for individual differences. The dependent variable in this analysis was the participants' presence score.

### *6.3.1 Results and discussion*

#### *Results*

The mean score of the 30 participants for the ITQ scale was 71.77 (SD=12.06, minimum and maximum scores at 51 and 96, respectively) with high reliability (Cronbach's $\alpha$=0.776). Participants' perceived self-efficacy score (M=30.57, SD=3.54), reflects an optimistic self-belief [152], such as that the participants could cope with adversity, e.g. teleoperating a robot sprayer. The reliability of the GSE was high, Cronbach's $\alpha$=0.836. Participants' mean score on the Santa Barbara Sense of Direction scale was M=4.95 (SD=0.93), which is above the scale's reported mean of 4.7 [85]. The SBSOD had high reliability, Cronbach's $\alpha$=0.809.

Table 13 summarizes the descriptive statistics of the dependent variables per factor (type of screen output, number of views and type of robot control input device). Details and the raw data from the experiment are available in Appendix II.

*Table 13. Dependent variables collected per examined user interface factors*

| Factors | Conditions | N | Grapes sprayed (0-24) | | Collisions | | Completion time (s) | | SUS score (0-100) | | Overall task load index (0-100) | | Presence questionnaire score | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | M | SD | M | SD | M | SD | M | SD | M | SD | M | SD |
| Number of views | Single view | 120 | 4.19 | 3.95 | 1.28 | 1.44 | 210.34 | 89.09 | 64.14 | 17.08 | 46.14 | 19.33 | 83.96 | 21.12 |
| | Multiple views | 120 | 14.03 | 7.39 | 0.51 | 0.81 | 239.24 | 129.32 | 64.39 | 18.14 | 43.38 | 16.60 | 89.49 | 19.27 |
| Robot control inputs | PS3 gamepad | 120 | 8.66 | 8.12 | 0.85 | 1.30 | 238.27 | 113.03 | 57.79 | 16.44 | 50.95 | 17.83 | 80.88 | 21.09 |
| | PC keyboard | 120 | 9.56 | 7.25 | 0.93 | 1.15 | 211.30 | 109.27 | 70.75 | 16.30 | 38.57 | 16.06 | 92.58 | 17.86 |
| Type of screen output | PC screen | 120 | 9.13 | 7.65 | 0.90 | 1.27 | 224.17 | 118.40 | 65.95 | 16.16 | 42.63 | 17.57 | 88.06 | 19.26 |
| | HMD | 120 | 9.09 | 7.77 | 0.88 | 1.18 | 225.41 | 105.18 | 62.58 | 18.81 | 46.89 | 18.31 | 85.39 | 21.41 |

*Effects of the three factors on actual and perceived usability*

GLMM were conducted on observed and perceived usability for the three factors (type of screen output, number of views and type of robot control input device). 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<0.000* and *F(1,232)=34.633, p<0.001*, respectively (Figure 22). Specifically for the spraying task, participants with the multiple views sprayed significantly more grape clusters (M=14.03 SD=7.39), compared to those with the single view (M=4.19, SD=3.95), with an effect size d=1.66. For the robot path navigation task, participants with the 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.

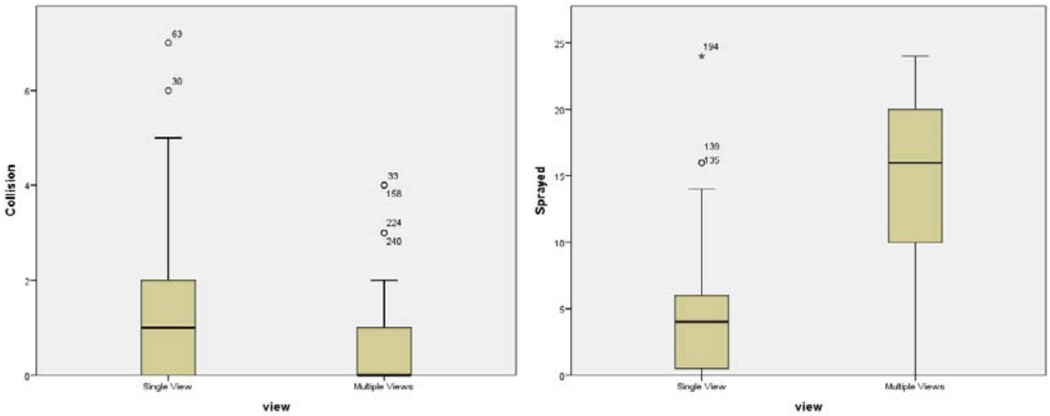



*Figure 22. HRI effectiveness with respect to the number of views*
*Left: Number of collisions, Right: Number of grape clusters sprayed*

In terms of HRI efficiency, a GLM (3-way ANOVA with repeated measures) was conducted on the three factors with measures on inverse time. The number of views and the robot control inputs 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. For the whole task (robot path guidance, identification of targets, and spraying), participants interacting with the robot using the PC keyboard and with the multiple views available (M=222.50, SD=116.21) required less time to complete the task, 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 robot control input devices: *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 [15], 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.

*Effect of the three factors on the subjective perceived workload and GSE*

To investigate whether the different interaction styles influenced the perceived work load index (NASA TLX), a 3-way ANOVA was performed where the three factors were within-subject-factors, with measures on NASA-TLX. There was a significant main effect of screen type on perceived workload index; $F(1,29)=4.92$ $p<0.05$, $\eta^2=0.145$. The PC screen contributed significantly less to the workload index compared to the HMD. There was also a significant main effect of the type of robot control input device; $F(1,29)=28.13$, $p<0.000$ , $\eta^2=0.492$. Specifically, participants using the PS3 gamepad reported a significantly higher perceived workload index score, compared to those using the PC keyboard. There was also a significant main effect in the interaction between type of robot control device and number of views on the perceived work load index; $F(1,29)=4.07$, $p<0.05$, $\eta^2=0.144$. Specifically, it was found that the perceived workload index does not depend on the value of the number of views but rather on the type of robot control tool. The PS3 controller increased the perceived workload index in both the single and multiple view condition (M=51.05 and M=50.87, respectively), while the PC keyboard had lower perceived workload index score, again for both the single and multiple views condition (M=41.25 and M=35.86, respectively). A LMM with repeated-measures on the three factors and the GSE score of the participants' as a covariate indicated that the GSE score was not a significant factor; $F(1,231)=1.37$, $P=0.24$; the only significant factors were the screen type and robot control input device $F(1,231)=6.34$, $P<0.01$ and $F(1,231)=53.71$, $P<0.000$, respectively.

*Effects of participants' immersion tendency on presence*

The Linear Mixed Model analysis results indicated that the type of robot control input device $F(1,228)=35.184$, $p<0.000$, as well as the number of views $F(1,228)=7.870$, $p<0.005$, are both significant factors influencing the perceived sense of presence. The type of screen output was not a significant factor for the presence dependent when participants' immersion tendency was used as a covariate. Likewise, the covariate (ITQ score) was not statistically significant $F(1,230)=0.003$, $p=0.957$. Regarding the type of robot control input devices when participants' were guiding the robot using the PC keyboard their perceived sense of presence was significantly higher (M=92.58, SD=17.86), compared to those who were using the PS3 gamepad (M=80.88, SD=21.09), with an effect size d=0.598. The participants' perceived sense of presence was also significantly higher when they had the multiple views user interface (M=89.49, SD=19.27), compared to when they had feedback from the single view camera (M=83.96, SD=21.12), with an effect size d=0.273.

*Effects of participants' sense of direction on actual and perceived usability*

GLMM were conducted on observed and perceived usability for the three factors (type of screen output, number of views and type of robot control input device). Regarding the participants' sense of direction, in relation to the three factors, it was found that the SBSOD score was not statistically significant. Specifically in terms of efficiency (time on task) the SBSOD was $F(1,231)=1.802$, $p=0.181$; regarding effectiveness, in relation to targets sprayed $F(1,231)=0.298$, $p=0.586$ and number of collisions $F(1,231)=0.223$, $p=0.637$). Finally in relation to perceived usability (SUS score) the SBSOD was again not significant $F(1,231)=0.418$, $p=0.518$.

### *Summary of results*

- Participants were more effective (i.e., had less collisions and sprayed more grape clusters), both in spraying and in robot path guidance, when they had the multiple views, than when they had single view; 60.16% and 234.84%, respectively.
- In single view, participants required significantly less time to complete the task, than when they had multiple views (12,08% difference).
- Using the PC keyboard required significantly less time to complete the task by 11.32%, compared to those using the PS3 gamepad.
- The PC keyboard had significantly higher perceived usability (SUS score) compared to the PS3 gamepad controller by 13 percentiles.
- Participants using the PC keyboard, reported a significantly lower perceived workload index, compared to those using the PS3 gamepad controller by 24.30%.
- With the multiple views and the PC keyboard condition, participants' perceived sense of presence was significantly higher, than when they had the single view and operated with the PS3 gamepad.
- The PC screen contributed significantly less to the workload index, compared to the head mounted display by 9.09%.

### *Discussion*

Two tasks were performed with the AgriRobot teleoperated sprayer system: path guidance (robot navigation) and spraying in open field (vineyard) conditions. Field study findings related to three user interface factors of the AgriRobot system; the type of screen-output (PC screen and HMD), the number of views (single view and multiple views), and the type of robot control inputs (PS3 gamepad and PC keyboard) are discussed in the following.

*Type of screen output:* This factor had influence only on the perceived workload index. Specifically, it was found that the PC screen contributed significantly less to the workload index, compared to the HMD. Lichtenstern, et al. [112] also reports several users' inconveniences with HMD and higher overall task load index, however they also found that this frustration decreases over the course of time. The type of screen output was not found to be significant for the presence covariate to the participants' immersion tendency. This may be because the users were actually having the same output/feedback just in different devices.

*Number of views:* Our results confirm findings from Yanco and Drury [188] who concluded that, "*when teleoperating a robot, operators rely on the video to determine the best way to navigate the environment*". In addition, Drury, et al. [49], concluded that "*a video centric interface is more effective in providing good surroundings and activities awareness*". Murakami, et al. [122] used an omnidirectional camera and a field map for the operator to observe the teleoperated vehicle during teleoperation. 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. Figure 23 illustrates the importance of the multiple views user interface, compared to the single view user interface. Operators driving the robot with a single camera could not be in a position to identify obstacles (bucket) in front of the robot wheels, nor could they easily identify grape clusters to spray. By contrast, operators with the multiple views user interface could identify both the obstacle and grape clusters to spray, much more effectively. These findings are in line with other research recommendations [98, 164].


(a) User interface with single view (b) User interface with multiple views

*Figure 23. Multiple vs single view factor*

*Left: single view from main camera, Right: multiple views from main, peripheral and end-effector target cameras*

*Type of robot control inputs:* The PC keyboard was found to be significantly superior to PS3 gamepad controller in terms of time to complete the task, perceived usability, perceived workload index and perceived sense of presence. However, all participants were far more experienced in using a keyboard than in using a PS3 gamepad controller. More experiments are needed to re-evaluate this factor and investigate how behavior changes along time, i.e. after using the robot control inputs for some time in which the user gains experience.

*Potential reasons for the observed task success rate (spraying):* The highest task success for spraying grape clusters (across conditions) was 58%. The result is in similar range to low performance of harvesting robots (average 66%) [12], when including all results. 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. Detection rate can be improved by incorporating more advanced detection algorithms and combining human in the loop [18]. Blackmore, et al. [30] argues that the 95% is the lowest barrier for the detection rate in order for the spraying process to be economically feasible. Correa, et al. [43] reported a 95% hit rate for red grape clusters but with artificial white background. A new version of the AgriRobot system will include automatic algorithms and human-robot collaboration to improve performance.

### 6.4. Laboratory experiment: HRI heuristic usability evaluation

The heuristic evaluation method was employed, as one of the most popular usability inspection techniques, which are also known as expert-based methods, user-free methods or methods performed in the lab without end-users. An adequate number of experts was found and recruited so that reliable evaluation results could be obtained.

First, the evaluators were informed about the system goal, its representative users and their typical tasks and the developers' design goals and expectations. The heuristics used for this experiment, were developed in a previous work [2] (presented in Chapter 5). Next, they used the system and conducted an individual heuristic evaluation according to a specific protocol, the selected set of heuristics appropriate for the evaluation context, and a template for reporting the identified usability issues. The evaluators were situated at the Hellenic Open University (HOU) Software Quality Assessment laboratory and controlled the robot remotely, which was located at the Open University of Cyprus (OUC), Nicosia premises. An appropriate lab-simulation environment was created, including various paths and targets. After each individual evaluation, the participating evaluators conducted a focus group to group and prioritize the identified usability issues.

***Participants***

Four usability experts – an adequate number to ensure reliable results [124] – conducted a heuristic usability evaluation on three user interfaces. All four have undergraduate and/ or postgraduate studies in Computer Science and extensive experience in the design and evaluation of interactive systems.

***Evaluated system***

Three user interfaces for the Semi-Autonomous Agricultural Robot Sprayer (SAARS) were evaluated: SAARSv0, SAARSv1, and SAARSv2. Figure 24 presents the three main screens of these user interfaces.

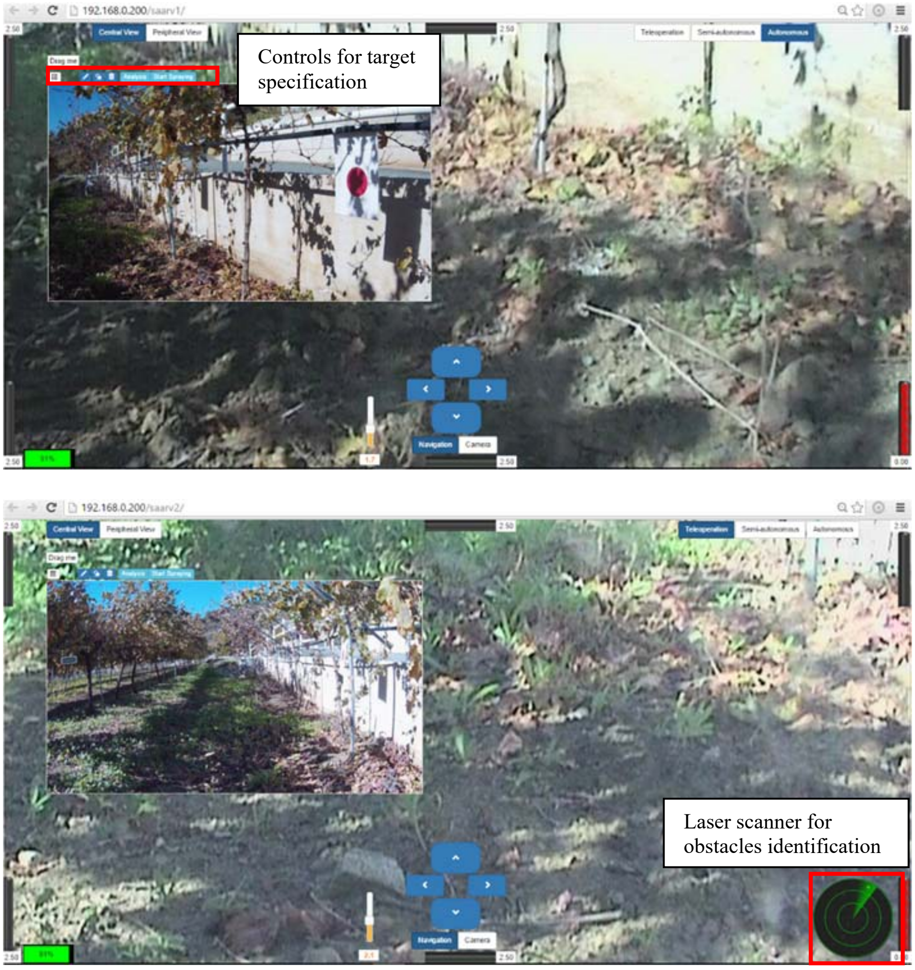



*Figure 24. The SAARS user interfaces under evaluation. Top: SAARSv0, Middle: SAARSv1, Bottom: SAARSv2.*
Note: The red rectangles and black text boxes are not part of each user interface

SAARSv0 is the redesigned user interface developed to support (non-semiautonomous) teleoperation of a robot performing agricultural work in the context of two research projects AgriRobot and SAVSAR (presented in Chapter 2). In terms of functionality, the main redesigns considered were: a) on-screen controls of the 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 SAARSv0, was to enable the operator to use the entire screen and support interaction through either the keyboard or the mouse.

SAARSv1, is an upgraded user interface of SAARSv0. It provides functionality for target pointing. In specific, SAARSv1 supports both manual (user points to targets) and automated target specification through a pattern recognition algorithm.

SAARSv2 is a redesigned user interface of the SAARSv1: it provides additional support in robot movement by displaying a radar control (bottom-right part of the user interface) with distances from obstacles around the robot.

The evaluators were situated at the Hellenic Open University Software Quality Assessment laboratory at Patra, Greece and remotely controlled (over Remote Desktop Connection) the robot, which was located in Cyprus at the Open University of Cyprus premises. An appropriate simulation environment was created, including various paths and targets.

***Procedures***

The same procedure was followed in all three heuristic evaluation studies. The following set of research-based heuristics for the design of robot teleoperation, which have been developed in Adamides, et al. [2] were used:

- *Platform architecture and scalability:* "Provide the flexibility to iterate robotic and computing technological developments in the user interface of the HRI system." The user interface of an HRI system should be flexible to follow and benefit from developments in computing and robotic technologies.
- *Error prevention and recovery:* "Provide information and alerts to avoid and recover from user errors." The information provided by the user interface should prevent user errors, and if a user makes a mistake, the user interface should allow for its rectification. In contrast with undoing a "Cut" operation in a word processor, a "Cut" command to prune a tree through a teleoperated AgriRobot cannot be undone.
- *Visual design:* "Provide an aesthetic, clear, and simple design of the user interface with the relevant information necessary." Since the user interface is the communication medium between the operator and the remote robot, it should provide the operator with only relevant information (from video and other robot sensors) in a simple, consistent, effective, and minimalist way. Specific examples include minimizing use of multiple windows, avoiding window occlusion, providing large video windows and displaying the robot's body in the interface.
- *Information presentation:* "Provide the necessary information, in the right context, moment, and modality." Controlling a remotely located robot is demanding on operators who need to integrate various sources of information coming from the robot cameras and sensors. Therefore, information presentation

is of high importance in this type of user interface designs, to enhance situation awareness of the operators, and to bridge the gaps of execution and evaluation [7].

- *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." The robot should be able to self-inspect its systems and take autonomous action or ask for user intervention. The human operator should have a clear understanding about the robot status and activities. For instance, to support understanding of the camera(s) and their position(s), the over-all mission and the current progress, and when multiple robots are available, use one to view another.
- *Interaction effectiveness and efficiency:* "Provide efficient and effective interactions between human and robot." In HRI, efficiency is measured in terms of the time required to complete a task; effectiveness is measured in terms of how well a task is completed.
- *Robot environment/surroundings awareness:* "Provide spatial information about the robot's surroundings and the environment where it is operating." Environment awareness is essential, because in field robot teleoperation it is important to have knowledge of the robot's whereabouts and the area covered, such as orientation, obstacles, or why a robot is not moving. This can be accomplished through maps, orientation information (such as compass), and sensors that will provide the necessary information about the robot's surroundings.
- *Cognitive factors:* "Use mental models and metaphors to lower the cognitive load." Cognitive factors are characteristics that affect performance and learning. The user interface of a teleoperated HRI system should be designed such that it directs the user's attention to the task the robot is operating, improves learnability, and provides fused information from the various sensors and cameras from the robot, in order to lower the cognitive load on the user.

Next, the evaluators were informed about the system goal, its representative users and their typical tasks. In addition, the developers of the system communicated their design goals and expectations.

Subsequently, each evaluator conducted a heuristic evaluation of the system. To this end, they were provided with access to the SAARS version under evaluation. They first familiarized themselves with the system by performing typical user tasks and exploring its functionality. Next, they inspected the system, identified usability issues and wrote them down following specific evaluation template. For each problem, they noted the heuristic violated and rated its severity on a scale from 1 to 5 (1=a little important, it does not significantly affect the user interaction, 5=extremely important, catastrophic problem that may result in unsuccessful task, danger to life or damage to property). In evaluating the severity of a usability problem, they were asked to take into account the following factors [125]: a) frequency, b) impact, and c) persistence. Finally, each evaluator was asked to provide a design suggestion for resolving the identified usability issue. The four evaluators produced individual reports with the identified usability issues per heuristic rule [2].

After each individual evaluation, the study coordinator and the evaluators participated in a focus group in order to produce the final list of unique problems, discuss on the final severity ratings and proposals for solutions; the coordinator produced the final report.

***Results***

Results of the heuristic evaluation (details in Appendix III) showed that the systems under evaluation provide very good (in terms of usability issues identified by experts) services to their expected typical users. A small number of usability problems were identified whose redress can improve the overall user experience with the system.

In the following, the results for each evaluated system are presented. The total number of expected problems for the each system was calculated using the formula [127]:

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

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.

*A. First user interface: SAARSv0*

For SAARSv0, 13 usability issues were identified. Most (77%) of these usability issues were related to violations of the following four heuristics: a) 23% were violations of heuristic 4 (Information presentation), b) 23% were violations of heuristic 5 (Robot state awareness), c) 15% were violations of heuristic 6 (Interaction effectiveness and efficiency) and d) 15% were violations of heuristic 8 (Cognitive factors). In terms of problem severity, the issues with the highest priority were related to violations of the following three heuristics: a) heuristic 5 (Robot state awareness) with the highest average severity (4.0), b) heuristic 2 (Error prevention and recovery) with the second from top average severity (4.0), and c) heurist 3 (Visual design) with also second from top average severity (4.0).

The expected number of usability problems for SAARSv0 was calculated to 42, which is above average number of usability problems (35) observed in a rather mature interactive system [127]. In addition, a substantial number of problems (9) were rated as 3+ on a severity scale from 1 to 5. The average severity of the identified problems is characterized as medium (3.3). All in all, the system is at a satisfactory level of usability. However, there are changes that could further improve its usability.

*B. Second user interface: SAARSv1*

Regarding SAARSv1, 10 usability issues were identified. Most (80%) of these usability issues were related to violations of the following four heuristics: a) 20% were violations of heuristic 4 (Information presentation), b) 20% were violations of heuristic 5 (Robot state awareness), c) 20% were violations of heuristic 6 (Interaction effectiveness and efficiency) and d) 20% were violations of heuristic 8 (Cognitive factors). In terms of problem severity, the issues with the highest priority were related to violations of the following three heuristics: a) heuristic 2 (Error prevention and recovery) with the highest average severity (4.0), b) heuristic 6 (Interaction effectiveness and efficiency) with the second from top average severity (3.0), and c) heuristic 5 (Robot state awareness) with third from top average severity (2.0).

The expected number of usability problems for SAARSv1 was calculated to 15, which is less than half the average number of usability problems (35) observed in a rather mature interactive system [127]. In addition, a small number of problems (3) were rated as 3+ on a severity scale from 1 to 5. The average severity of the identified problems is characterized as low (2.1). These findings tend to provide support that the system is at a good level of usability.

C. Third user interface: SAARSv2

Regarding SAARSv2, three usability issues were identified. These issues were related to violations of the following three heuristics: a) one violation of heuristic 3 (Visual design), b) one violation of heuristic 6 (Interaction effectiveness and efficiency), and c) one violation of heuristic 7 (Robot environment/surroundings awareness). In terms of problem severity, violation of the heuristic 7 (Robot environment/surroundings awareness) had the highest average severity (2.0), followed by violations of the heuristic 3 (Visual design) and heuristic 6 (Interaction effectiveness and efficiency) which were both rated with an average severity of 1.0.

The expected number of usability problems is 4, which is a lot less than the average number of usability problems (35) observed in a rather mature interactive system [127]. In addition, all the identified issues were rated as 2- on a severity scale from 1 to 5. The average severity of the identified problems is characterized as very low (1.3). All in all, the system is at a very good level of usability.

***Discussion***

The heuristic evaluation studies indicated that the expected number of usability issues was 42 for SAARSv0, 15 for SAARSv1 and 4 for SAARSv2 respectively. According to [127], the average number of usability problems observed in a rather mature interactive system being 35. In addition, the average severity of the identified usability issues was characterized as medium (3.3) for SAARSv0, low (2.1) for SAARSv1, and very low (1.3) for SAARSv2 respectively.

According to the expert evaluators, one important advantage of all the SAAR user interface versions is that they take full advantage of the screen size providing a large window for the central and peripheral views. In addition, the user can easily customize the placement and size of the end-effector camera view. Furthermore, implicit switching of autonomy level is supported, but it should be better communicated to the user. Moreover, important information, such as the exact distance from obstacles and the remaining battery level, are always available. However, equally important information, such as the remaining level of spraying liquid (the robot is used to spray vineyards), is not available at all.

SAARv1 and SAARv2 support functionality for targeted spraying in a rather intuitive way. However, there are user interface improvements that could be made in the manual target addition and deletion to better reflect what the user is doing. In addition, these systems provide support for automated target identification, which may lead to increased efficiency in the actual field. However, the associated dialogue for changing the algorithm settings is in a highly technical and complicated language for the typical user. Finally, SAARv2 has one additional advantage: it provides the radar control that may support effective and efficient obstacle avoidance.

However, there is always room for improvement. The expert evaluators argued that the next version of the system could benefit from:

a) An embedded representation of the robot's body in the user interface displaying sensor information and robot direction in relation to the active camera views (heuristic 7),
b) Embedded help explaining functionality and controls (heuristic 8), e.g. simplify and explain algorithmic settings for automated target identification, embed tooltips and/or labels on the buttons related to user-defined targets,
c) Mechanisms for error prevention in target identification and spraying (heuristic 2), e.g. confirmation message for the "erase-all-targets" action,
d) Additional information that is important for the task (heuristic 4) e.g. remaining level of spraying liquid,
e) Improvements in the visual design of the user interface (heuristic 3), e.g. visual clarification for currently active control, larger text labels to increase readability.

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. This can be attributed to the iterative design, development and evaluation process followed for the SAAR system in the context of the SAVSAR research project. The abovementioned advantages, combined with the increased usability of the SAARv2 (final) system, may result in high adoption from its end users.

### 6.5. Field user experience testing of the final SAARS user interface

The main goal of this experiment was to evaluate the user experience of the final version of the user interface (SAARSv2). 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, 2 female with an average age of 38.8. This number of participants is adequate to uncover the most important usability issues [169], 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 [35] and UEQ [108] 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 [15], 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 [108] showed that SAARSv2 was perceived as "excellent" in terms of attractiveness, perspicuity, efficiency, dependability, and stimulation, and "good" in terms of novelty. All in all, SAARSv2 was rated among the 10% best results in all but one (novelty) of the subscales (Figure 25).

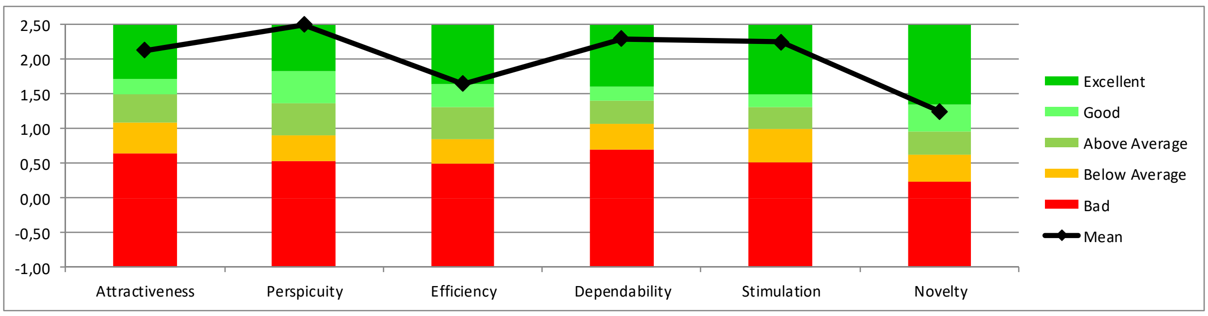



*Figure 25. Comparison of this research study UEQ data with benchmark UEQ data [159]*

### 6.6. Contribution

This chapter presented several HRI usability evaluation experiments conducted on a semi-autonomous agricultural robot sprayer. Four studies were conducted: two in the open field (vineyard) and two in a laboratory setting. The main contribution of this chapter is essentially the findings of these studies which are summarized below:

A 2x2x2 repeated measures experiment was conducted with the following factors under examination: the *type of screen output*, PC screen and Head Mounted Display (HMD), the *number of views*: single view and multiple views, and the *type of robot control inputs*: PS3 gamepad and PC keyboard. The usability of eight different combinations was evaluated by measuring users' interaction effectiveness, interaction efficiency and overall satisfaction. The experiment took place at the vineyard experimental station of the Agricultural Research Institute at Saittas, Cyprus. The following results were found:

- Participants were **more effective** (i.e., had less collisions and sprayed more grape clusters), **both in spraying and in robot path guidance**, when they had **the multiple views**, than when they had single view; 60.16% and 234.84%, respectively.
- In **single view, participants required significantly less time to complete the task**, than when they had multiple views (12,08% difference).
- Using the **PC keyboard required significantly less time to complete the task** by 11.32%, compared to those using the PS3 gamepad.
- The **PC keyboard had significantly higher perceived usability** (SUS score) compared to the PS3 gamepad controller by 13 percentiles.
- Participants using the **PC keyboard**, reported a significantly **lower perceived workload index**, compared to those using the PS3 gamepad controller by 24.30%.
- With the **multiple views and the PC keyboard condition**, participants' **perceived sense of presence was significantly higher**, than when they had the single view and operated with the PS3 gamepad.
- The **PC screen contributed significantly less to the workload index**, compared to the head mounted display by 9.09%.

The heuristic evaluation method was employed, as one of the most popular usability inspection techniques, which are also known as expert-based methods, user-free methods or methods performed in the lab without end-users. Three user interfaces were developed and examined: **SAARSv0** is the redesigned user interface developed to support (non-semiautonomous) teleoperation of a robot performing agricultural work. **SAARSv1**, provides functionality for target pointing. Finally, **SAARSv2** provides additional support in robot movement by displaying a radar control (bottom-right part of the user interface) with distances from obstacles around the robot. The expert evaluators argued that the next version of the system could benefit from:

- An **embedded representation of the robot's body in the user interface** displaying sensor information and robot direction in relation to the active camera views (heuristic 7),
- **Embedded help** explaining functionality and controls (heuristic 8), e.g. simplify and explain algorithmic settings for automated target identification, embed tooltips and/or labels on the buttons related to user-defined targets,
- **Mechanisms for error prevention in target identification and spraying** (heuristic 2), e.g. confirmation message for the "erase-all-targets" action,
- **Additional information that is important for the spraying task** (heuristic 4) e.g. remaining level of spraying liquid,
- **Improvements in the visual design** of the user interface (heuristic 3), e.g. visual clarification for currently active control, larger text labels to increase readability.

In conclusion, the findings, from both the field and the lab experiments, provide evidence that the final version of the system with minimum improvements could provide satisfactory services to its typical users.

# Chapter 7. Conclusions and future work

**Chapter overview**

This chapter presents a summary of the research findings, a discussion of the main results, and future research directions related to this research that focused on human-robot interaction aspects for semi-autonomous agricultural robot operation. The research was applied for a teleoperated sprayer focusing on the user interface design and its usability evaluation.

### 7.1. Summary of findings

***Robot design***

The methodology followed to transform a generic mobile robotic platform to an agricultural robot sprayer was presented, addressing both hardware and user interface design aspects and related problems faced and solutions provided. Placing cameras on the end-effector (nozzle sprayer) and supporting peripheral vision (camera on the back top of the robot) improved surroundings and activity awareness.

***Taxonomy***

A significant work done in this dissertation has to do with the development of a taxonomy of human-robot interaction usability heuristics. The taxonomy was developed from a focused literature review on robot teleoperation user interface design guidelines. The taxonomy was generated using the card sorting procedure. Both the open and the closed card sorting methods were used in an experiment which involved experts from the related fields (usability, user experience, information architects, HCI and HRI). The taxonomy consists of eight distinct categories: 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 surroundings/ environment awareness, and 8) cognitive load. Such a taxonomy should be valuable to other researchers, information architects, usability experts, and to developers, especially those interested in the design and evaluation of teleoperated mobile field robots.

***Framework for semi-autonomous operation***

Semi-autonomous mode is the mode of operation where one or more operations are in manual mode and one or more operations are in autonomous mode. The robot has operations both in manual and in autonomous modes, concurrently. This formal framework brings out human-robot interaction theoretical issues and more practical issues specific to the user interface design framework.

***Usability***

Aside from knowing the issues and goals described above, the first step was to determine how to begin work in this research area. Without the resources to experiment in the field as a first step, we used an effective test-bed - a simulation experiment in a lab – to evaluate the usability of three different input devices. The goal was to evaluate the selection input device (Mouse vs Wiimote vs Digital pen) for marking the targets (grape clusters). Results indicated usability preference for the mouse and the digital pen. The log files analysis revealed that the participants were most effective and efficient when using the digital pen as compared to the mouse and the Wiimote.

A semi-autonomous robot sprayer was custom built on top of an operating mobile robot following a methodological approach. A first version was designed installing a sprayer tank and a canon nozzle end-effector. Initial experiments in the field revealed issues with navigation and the spraying task. Specifically, it was difficult to navigate the platform in a path due to limited field-of-view. Additionally, the two cameras on the robot platform did not provide sufficient feedback on the spraying task. To solve these two issues, a second version of the robotic platform was designed to include an extra camera on the end-effector sprayer nozzle to provide spraying feedback, and another camera at the back-top of the robot to provide peripheral vision around the robot wheels.

The main experiment of this work took place in an actual vineyard field. A 2x2x2 repeated measures experiment was conducted examining the following factors: the type of screen output (PC screen vs. Head Mounted Display, HMD), the number of views (single view vs. multiple views), and the type of robot control inputs (PS3 gamepad vs. PC keyboard). The usability of eight different combinations was evaluated by measuring users' interaction effectiveness, interaction efficiency and overall satisfaction.

The main findings related to the user interface design were:

- Participants were 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, as compared to when they had single view;
- Participants required significantly less time to complete the task when they had the single view as compared to when they had multiple views;

- Using the PC keyboard required significantly less time to complete the task compared to those using the PS3 gamepad;
- The PC keyboard had significantly higher perceived usability (SUS score) compared to the PS3 gamepad controller;
- Participants using the PC keyboard, reported a significantly lower perceived workload index, compared to those using the PS3 gamepad controller;
- With the multiple views and the PC keyboard condition, participants' perceived sense of presence was significantly higher, than when they had the single view and operated with the PS3 gamepad.
- The PC screen contributed significantly less to the workload index, compared to the head mounted display.

The aforementioned findings provided strong evidence that the feedback from the peripheral and end-effector cameras are valuable and contribute to the effectiveness of the spraying and navigation task.

Based on the proposed taxonomy, a heuristic evaluation method was employed to evaluate the usability of the three user interfaces that were developed during this time. The expert evaluators argued that the next version of the system could benefit from:

- An embedded representation of the robot's body in the user interface displaying sensor information and robot direction in relation to the active camera views (heuristic 7),
- Embedded help explaining functionality and controls (heuristic 8), e.g. simplify and explain algorithmic settings for automated target identification, embed tooltips and/or labels on the buttons related to user-defined targets,
- Mechanisms for error prevention in target identification and spraying (heuristic 2), e.g. confirmation message for the "erase-all-targets" action,
- Additional information that is important for the spraying task (heuristic 4) e.g. remaining level of spraying liquid,
- Improvements in the visual design of the user interface (heuristic 3), e.g. visual clarification for currently active control, larger text labels to increase readability.

In conclusion, the findings, from both the field and the lab experiments, provide evidence that the final version of the system with minimum improvements could provide satisfactory services to its typical users.

### 7.2. Discussion

Both field and laboratory experiments investigated HRI design aspects of agricultural spraying robots. Field experimental results confirm findings from Yanco and Drury [188] who concluded that, "*when teleoperating a robot, operators rely on the video to determine the best way to navigate the environment*." In addition, Drury, et al. [49], concluded that "*a video centric interface is more effective in providing good surroundings and activities awareness*". Likewise, Murakami, et al. [122], used an omnidirectional camera and a field map for the operator to observe the teleoperated vehicle during teleoperation. 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.

Designing usable human-robot interactions support operators to perform complex tasks [55, 181]. Effectiveness is 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 communication needs, building a trust for cooperation and collaboration spirit between human and robots.

The work described in this dissertation summarizes an approach to understand the need for human-robot collaboration/interaction specifically for mobile 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), defining levels of autonomy (including levels and type of communication), 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. Obviously, the findings of this work are not limited to agricultural robot sprayers alone; rather they are applicable to other agricultural tasks as well, such as harvesting robots. I also posit that the heuristics and user interface guidelines, proposed in this work, are generalizable enough to apply to other mobile field robots applications.

### 7.3. Future research directions

The current robot sprayer system is limited in its small size (both in relation to the platform and the sprayer tank), as shown in Figure 26. Such a system (AgriRobot) can be used inside a greenhouse. For field operations a bigger platform (e.g. tractor) and sprayer tank are needed. An alternative solution to be considered is the robotization of a tractor. In this case, the tractor can be used for several agricultural tasks which could enhance its financial feasibility.

*Figure 26. Left a tractor sprayer, Right: the AgriRobot sprayer*

Multi-tasks performed by a single robot can add to economic feasibility similar to the Da Vinci Robotic Surgical system [139]. The system consists of an ergonomically designed surgeon's console, a patient-side cart with robotic arms which can handle a number of surgical proprietary EndoWrist instruments, and a high-performance vision system (3-D). An agricultural robotic platform would be economically feasible [137] if it can do more than one tasks [80] (i.e. by having multiple robotic arms or one robotic arm that can handle multiple agricultural instruments).

In the case of a new robot with a robotic arm installed and additional sensor capabilities (laser and LIDAR scanners) – as in the case of http://www.savsar.gr - a new user interface should be developed, following the taxonomy guidelines, and experiment with other teleoperation equipment (i.e. joystick) as well. Another major field experiment should be designed to evaluate the new system.

Endalew, et al. [56] mentions that operators can quickly become disoriented when when tele-operating a mobile robot using rate-control (hand controllers) and video feedback,. On the other hand, adolescences are used to play video games daily for long hours [14, 179]. Therefore, it is also worthwhile to put into test the fatigue factor in various human-robot collaboration levels; how is the user performance and workload affected after using the developed human-robot system for long hours?

In terms of user interface technologies, with the emergence of new sensor technologies and 3D cameras improvements, it would be worthwhile to develop user interfaces with augmented reality capabilities to investigate their effect on situational awareness of operators when using tele-robotics.

A formal framework regarding the transition between the levels of autonomy when the user intervenes in the robot operation was defined. This framework was implemented on the user interface of the developed system but needs to be tested in future experiments and validate results. It would be interesting to apply this framework to other related work in human-robot collaboration research [18] including switching between collaboration levels [80].

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# Appendices

# Appendix I

**Pointing devices experiment**

1) The flash simulation executable file that was used during the pointing devices (mouse, Wiimote, digital pen) experiment, is available here:

https://www.dropbox.com/s/u6bvxwrdxqlbmjw/agrirobot_v6.exe?dl=0

2) The log file (Microsoft Excel) with the raw results of the experiment is available here:

https://www.dropbox.com/s/zfnhklk2mujixj1/COMPLETE_RAW_DATA_logfile-agrirobot-flash_experiment_results.xlsx?dl=0

# Appendix II

**HRI usability evaluation – Major Field experiment**

1) The pre-experiment online questionnaire that was used during the major field experiment, is available here:

https://www.dropbox.com/s/flsjl3udw3i2zd8/LimeSurvey%20-%20Agrirobot_%20preExperimentQuestionnire.pdf?dl=0

2) The post-experiment online questionnaire that was used during the major field experiment, is available here:

https://www.dropbox.com/s/rxc3s2h225n2gyu/LimeSurvey%20-%20Agrirobot_PostExperimentQuestionnaire.pdf?dl=0

3) The data sheet (Microsoft Word) that was used during the major field experiment to collect actual usability metrics, is available here:

https://www.dropbox.com/s/uq1safyhhglf28g/agrirobot_fieldtest_datasheet_vfinal.docx?dl=0

4) The NASA-TLX online questionnaire (translated to Greek) that was used during the field experiment is available here:

https://www.keithv.com/software/nasatlx/nasa-tlx-greek.html

5) The data file (Microsoft Excel) with all the raw results of the major field experiment, is available here:

https://www.dropbox.com/s/pf5cs9usgp7gjg8/AGRIROBOT_ALL-questionnaire-dataEntry.xlsx?dl=0

# Appendix III

**Taxonomy experiment**

1) The online open card sorting experiment raw data (Cards, Categories, Results Matrix, Popular Placements Matrix), are available here:

https://www.optimalworkshop.com/optimalsort/4625634/45802he1/shared-results/a4150ba6d20f74d62f4ee578a27a7560

1) The online closed card sorting experiment raw data (Cards, Categories, Standardization Grid, Similarity Matrix, Dendrograms, PCA), are available here:

https://www.optimalworkshop.com/optimalsort/4625634/e02557/shared-results/4c451f4b0815f0ad7637263c45275cc9