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Ummi Noor Nazahiah binti Abdullah

NOVEL METHODS FOR ASSESSING AND IMPROVING USABILITY OF A REMOTE-OPERATED OFF-ROAD VEHICLE INTERFACE

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Supervisor Professor Heikki Handroos
LUT School of Energy Systems
Lappeenranta-Lahti University of Technology
Finland

Reviewers Prof. José Orlando Gomes, CPE
School of Engineering
Federal University of Rio de Janeiro
Brazil

Assoc. Prof. Ir. Ts. Dr. Abdul Rahim bin Abu Talib
Faculty of Engineering
University Putra Malaysia
Malaysia

Opponent Assoc. Prof. Ir. Ts. Dr. Abdul Rahim bin Abu Talib
Faculty of Engineering
University Putra Malaysia
Malaysia

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Abstract

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Autonomous control systems have been under intensive development in the off-road vehicle (ORV) industry because of high demand for increasing productivity in recent decades. In those systems, the progress has happened in particular in the container handling and mining industries, while some safety critical functions are still carried out by using remote operation by a human driver. The remote-operated station itself has its own issue, which is its lack of direct motion feeling, due to the loss of physical interaction and experience between the operator and the machine. The objectives of this thesis are to assess the user experience (UX) of existing remote-control interfaces, to establish a method for developing a list of design metrics based on UX goals, to assess the effects of haptic feedback as a technological solution, and to evaluate the usability of interfaces with haptic feedback by utilizing simulation and a virtual environment.

Firstly, a methodology using the User-Centered Design (UCD) approach was established to explore and investigate the UX in human-machine interaction in order to obtain the UX goals in the remote-operated control of an ORV. The UX investigations were administered in a real working environment at two international cargo terminals that use a remote-operated station (ROS) for controlling and handling the container cranes in the terminal blocks. The data from UX investigations was analyzed using modern software to produce the related results and UX goals. Secondly, a methodology to establish a list of design metrics based on UX goals was developed. Thirdly, an investigation methodology using virtual environments and real-time simulators with haptic interface for assessing the effects of haptic feedback as a solution for UX goals, and the list of design metrics in relation to the user’s age, gender and the effect of resting on a remote-operated ORV work shift was developed. Finally, a methodology to test the usability of haptic feedback from an ORV remote-operated control interface using the virtual environments and real-time simulators was developed. This usability testing measured the effectiveness, efficiency, and satisfaction of haptic interface system in ORV remote control and handling operation. Human-in-loop (HiL) virtual models by Mevea Simulation were run to study both the haptic feedback effect and the usability testing process. The simulations were run in the virtual environment of the Laboratory of Intelligent Machines at Lappeenranta University of Technology. A haptic feedback system connected with the control interface of a virtual simulation model of an automated rubber-tired gantry (A-RTG) was utilized in this investigation process.

At first, six UX goals for ORV remote-operated control interface design were developed based on eight positive experiences, eight negative experiences, and improvement suggestions. Next, a list of design metrics was established based on the two highest-ranking UX goals. Haptic feedback was suggested in the list of design metrics as one of the solutions for UX goals. Therefore, haptic feedback was investigated in an ORV remote-operated control interface and the results showed a significant difference in haptic feedback between two age groups. The average haptic feedback was 0.1225 N among participants below 30 years of age and 0.4455 N for those above 30 years of age. In addition, the usability testing results showed that the mean value for haptic joystick effectiveness was 46.31 cycles and for a normal joystick was 46.19 cycles in 10 minutes of operation. The mean efficiency when using a haptic joystick was 8.001 s, compared to 7.888 s when using a normal joystick. Finally, on average, user feedback for satisfaction was rated at the second point of the assessment scale (the haptic joystick was considered *very good* with regard to satisfaction) for the haptic joystick.

This thesis provides a novel method for investigating the UX for a remote-operated control interface in an ORV application. This thesis also proposes novel UX goals such as reduced time delays, problem detection, communication options, reduce visual limitations, handling smoothness, and ergonomics to be considered in a preliminary stage of autonomous control interface design for ORV. A novel list of design metrics for autonomous control interface design based on UX goals of problem detection and communication options is produced in the thesis, which contributes to important parameters for similar types of remote-operated control interfaces. The results from haptic feedback investigation as a solution to the UX goals of problem detection and communication options for the remote-operated control interface of ORV show that the haptic feedback force is closely related to the user's age. It can be concluded in this thesis that the autonomous control interface with haptic feedback almost maintains the same user performance as the normal autonomous control interface for simple tasks, while improving the safety aspect in remote operation such as a lack of direct motion feeling due to the loss of physical interaction and experience between the user and the machine.

UX goals such as reduced time delays, reduced visual limitations, handling smoothness, and ergonomics for autonomous control interface design of ORV will be investigated further in the future. In addition, the effects of haptic feedback on different age groups need to be examined further in association with the health status of the interface user. The usability testing of a haptic feedback control interface for ORV is strongly recommended for complex control operations in the future, to assess haptic control interface usability in complex tasks.

Keywords: autonomous control, user-centered design, user experiences, ethnography, engineering design, remote-operated, joystick interface, off-road vehicle, container crane, haptic feedback, usability testing, human-in-loop, real-time simulation, virtual environment

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I put effort into completing this D.Sc study and thesis. However, it would not have been possible without the kind support and help of many individuals and organizations. I would like to extend my sincere thanks to all of them.

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Most importantly, my strength to complete this study came from a lot of love from my husband Mohd Azhan Razali. He is the only man who could have survived my up-and-down journey, which was surely not an easy task. Also, thanks to my four darlings—Nurisma Fatimi, Isma Hasani, Isma Husseini, and Nurisma Masyitoh—who always keep me sane and alive. I hope our experiences in Lappeenranta will give them different perspectives in their own lives.

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Finally, without the wishes and power of almighty God, nothing is possible for me.

Ummi Noor Nazahiah binti Abdullah
December 2019
Lappeenranta, Finland

Dedication

To my husband Mohd Azhan Razali and
my children Fatimi, Hasani, Husseini, and Masyitoh

Contents

Symbols and Abbreviations

ASC	Automated stacking crane
A-RTG	Automated rubber-tired gantry
ATV	All terrain vehicle
ERA	Ergonomics risk analysis
GUI	Graphical user interface
HiL	Human-in-the-loop
ISO	International Organization for Standardization
NRMM	Non-road mobile machinery
ORV	Off-road vehicle
PSSUQ	Post-study system usability questionnaire
QFD	Quality function deployment
R&D	Research and development
ROCC	Remote-operated container crane
ROS	Remote-operated station
UCD	User-centered design
UI	User interface
UX	User experience

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1 Introduction

1.1 Background and motivation

This research deals with design and development concerns in off-road vehicle (ORV) applications in particular, with the aim of developing novel methods for assessing and improving usability of a remote-operated vehicle interface.

An ORV is generally defined as a vehicle that can be operated off-road and in multi-terrains (for example, in mining areas, harbor blocks, construction sites, farms, etc.) that have specific terrain and environmental characteristics, such as rough terrain, bad weather, large obstacles, and hazardous air [1]. Other researchers have used the terms *mobile machinery* or *non-road mobile machinery* (NRMM) in their studies e.g., Rozbahani and Luostarinen [2–4], in order to describe such vehicles. In relation to the usage environment and its function, the human factors and engineering specifications considered in designing an ORV are very different to those considered for on-road or domestic vehicles [5, 6].

ORV design and development in heavy industries is currently experiencing a major evolution, from human-operated systems to automated systems. This evolution is encouraged by many factors, such as a shortage of skilled operators, cost reduction [7, 8], performance improvement [9], and the very important factor of health and safety issues [6]. Previous and ongoing investigations regarding health and safety issues have produced remote-operation stations (ROSs) in autonomous control systems to control ORVs remotely, such as those that are implemented in container crane control and handling operation systems [10–17].

Nonetheless, after several years of ROS application in a container crane control and handling system, a lack of a direct motion feeling among remote operators has been identified, referring to the loss of physical operating experience between the operator and the crane mechanism, i.e., vibration through the seat. In addition, the operator has to depend solely on the limited monitor views that are equipped with the ROS to control and handle the cranes. This lack of direct motion feeling could lead to less safe handling operation [18] and endanger other people in the terminal blocks.

Most of the previous research on this subject has focused on developing the control system, such as studies by Gustafsson, Dadone, Aoustin, and Villaverde [16, 19–21], and the visual interface system, such as studies by Karvonen and Kaasinen [10, 18, 22] of the ROS, improving the mapping and navigation of remote-operated ORVs by Mousazadeh [23], and conducting a human factors comparison between commercial and heavy vehicles by Nowakowski [24] in order to enhance the machine and operators' performance. However, there is a gap in translating the UX into the related engineering parameters when developing the ORV. The first research into such control systems was done by Gustafsson and Heidenback [16], who investigated a remote-operated overhead bridge crane application where an electronic load control controlled the motion and path of a load suspended by wire ropes; automatic crane control was used to identify obstacles and the position of objects by scanning, guiding, and automatically sequencing the crane’s movements. The author also examined the anti-sway control and crane skew control in his study. The second research paper on this topic was conducted by Dadone and Vanladingham [19], which focused on the open-loop control method, based on a phase-plane analysis of the linearized model for moving the load of a gantry crane into a desired position in the presence of known, but arbitrary, motion-inversion delays, as well as there being cart acceleration constraints. The author found that the method had been limiting residual oscillations to less than one degree of amplitude, and the analytical results provided the fundamental knowledge to develop a controller for the suppression of load oscillations in ship-mounted cranes in the presence of arbitrary delays. Aoustin [20] had conducted an analytical and numerical study of the control problem of a gantry crane. The author used a quasi-time-optimal control law with force applied to the crane trolley as a controlling parameter. The results of the study showed that the method of anti-swing feedback control design can be recommended for a gantry crane control system. Finally, Villaverde et al. [21] investigated the remote-operating configuration of an electromechanical system, operated via the internet in a gantry crane application. The author suggested that the virtual and haptic feedback in a virtual environment, in combination with passivity-based control techniques, produced safe and robust remote-operated crane activities and increased performance, even with large and variable time delays.

Another field of study regarding remote-operated crane applications is on the visual interface system that was investigated by Karvonen et al. [18], relating to a work-demand comparison between the conventional and remote operation of a crane using the core-task analysis method. The researcher presented results that emphasized the importance of a comprehensive and coherent operating view, as well as the development of the rich and realistic feel of a visual interface system for a remote-operated crane. Then, the same authors, Karvonen et al. [10], continued the study by focusing on comparing the UXs of two different user interface concepts and giving feedback on how well the UXs goals—such as safe operation, a sense of control, and a feeling of presence—were being fulfilled by implementing the usability methods in ROS prototype testing. In a study relating to the experience-driven design of a remote-operated crane, Kaasinen et al. [22] reported that the literature study and experience-design process method resulted in achieving the UX goals (i.e., brand, theory, empathy, technology, and vision) for ROS design for crane applications.

A previous study, conducted by Mousazadeh [23], used the literature survey method in order to search for performance issues in the navigation system of a remote-operated vehicle. The author found that mapping, navigation, and obstacle detection are important issues to examine in remote-operated vehicle design. The human factors in heavy vehicle automation—such as basic motivations, institutional considerations regarding system design, driver training, and the transformation challenges in transforming from conventional design to automated design related to human aspects—were discussed by Nowakowski et al. [24].

The demands for the safety level of the control systems of an ORV are set at a significantly higher level if the vehicle is supposed to operate autonomously [26]. However, commercial-level state-of-the-art remote-operating systems only provide visual and auditory feedback from the machinery [25]. As a result, this motivated this study to explore more options to solve the issue of a lack of direct motion feeling among remote operators in remote-operated ORV applications by combining the user-centered design approach, engineering design approach and user testing approach in developing novel methods for assessing and improving the usability of a remote-operated ORV interface. The UCD became the fundamental approach to developing an exploration method for user experiences (UXs) investigation among industry operators and producing the UX goals for solving the lack of direct motion feeling issue. Next, the engineering design became the fundamental approach to developing a method to translate the prioritized UX goals into a set of possible, precise, and measurable technical parameters that would lead to usability and the satisfaction of the associated user experience and needs. Finally, user testing became a fundamental approach to developing an experimental method of testing to evaluate the haptic force as one of the technological solutions for the lack of direct motion feeling issue, and to evaluate the usability of haptic feedback and a haptic joystick in the remote-operated ORV application as well.

1.2 Objectives

The first aim of this doctoral thesis was to develop a novel method to investigate the UX in human-machine interaction in order to obtain the UX goals in an ORV remote-operated control interface.

The second aim was to establish a method for developing a list of design metrics based on UX goals.

The third aim was to develop a novel method for assessing the effects of haptic feedback as one of the solutions for UX goals and the list of design metrics by using virtual environments and a real-time simulator.

The fourth aim was to develop a method to test the usability of the haptic feedback control interface of an ORV using virtual environments and a real-time simulator.

1.3 The scope of the works

ORV in this study does not extend to all-terrain vehicles (ATVs), underwater vehicles, and aerospace vehicles due to their distinct functions, features, human factors, and engineering characteristics. This study was conducted for an ORV application that focused on a remote-operated control system. The objectives of this doctoral thesis are divided into two. The first aim is to show that the R&D process accounting for UX contributes significant and highly relevant attributes in ORV design. The second aim is to assess influence factors and the usability of the haptic feedback interface in a remote-operated control system environment. The fundamentals of this study relate to UX, ethnography and haptic theories. The control interface and the haptic feedback system were utilized to assess the influence factors and the usability of haptic feedback.

1.4 Scientific contribution

The main scientific contribution of this study lies in the research of processes for designing a remote-operated control interface of ORV to take advantage of the virtual environment, a real-time simulation and a haptic simulator.

1. An R&D process for a remote-operated control system of an ORV is developed in a real operation environment. The approach is novel because the kinesthetic aspect in studying such systems is not taken into account in studies by other researchers. Previous research examined visual aspects for monitor activities in order to improve working performance. The results demonstrate significant UX goals for the remote-operated control interface of ORVs such as time delay, problem detection, communication options, visual limitation, handling smoothness, and ergonomics. In addition, the results present a significant list of design metrics for UX goal solutions for remote-operated control interface design of ORVs.

2. A novel process for assessing the effects of haptic feedback in remote control operation as a solution to selected UX goals and the list of design metrics was developed. Usability tests and analyses were conducted by utilizing the proposed usability assessment methods, the real-time multibody simulator of the container crane, and a haptic prototype interface. The entire research set-up is novel and has not been studied previously by other researchers.

1.5 Author’s publications based on the results of the dissertation

An article with the title “Investigation on user experience goals for joystick interface design” [26] was presented at the 5th International Conference on Advances in Mechanical Engineering and was published in the Journal of Mechanical Engineering. This journal is listed in the 0-level JUFO ranking and the Q1 Scopus Index. The study aimed to establish some insights into how to improve the lack of direct motion feeling through a joystick interface in a remote-operated container crane application.

An article with the title “Investigation on sense of control parameters for joystick interface in remote-operated container crane application” [27] was presented at the 3rd International Conference on Green Design and Manufacture, and published in the AIP Conference Proceedings. This journal is listed in the 1-level JUFO ranking and the Q1

Scopus Index. The paper examined the parameters for developing the engineering parameters related to the sense of control goal in ORV remote-operated control interface design.

An article with the title “Investigation on sense of presence experience parameters for joystick interface in remote-operated container crane application” [28] was presented at the 6th International Symposium on End-User Development and published in the 6th International Symposium on End-User Development Extended Abstract. The paper examined the parameters to developing the engineering parameters that related to the sense of presence goal in the remote-operated control interface design of ORV.

An article with the title “Usability study in haptic control and handling interface design for remote-operated container crane application” [29] was presented at the 5th International Conference of Southeast Asian Network of Ergonomics Societies (SEANES 2018) and was published in the SEANES 2018 Proceedings. The paper investigated the usability of haptic feedback and its interface as a solution to selected UX goals for remote-operated control interface design of ORV.

1.6 The outline of the thesis

Chapter 2 presents a state-of-the-art review of the principles of user-centered design (UCD), UXs, ethnography, engineering design, haptic feedback, and usability testing.

Chapter 3 propose a process for UX investigation and analysis, a process for establishing a list of design metrics, a process to assess the effects of haptic feedback on users in remote control operation, and a process to test the usability of haptic feedback and its interface in remote-control interface of ORV.

In Chapter 4, the results of each process such as UX goals, a list of design metrics, effects on haptic feedback system, and usability testing are presented and discussed in detail.

In Chapter 4, the findings in this study are justified.

In Chapter 5, the conclusions and recommendations for future research are presented.

2 The state of the art

2.1 Human factors in design

Ergonomics, or human factors, is the scientific discipline concerned with the understanding of interactions among humans and the other elements of a system, and the profession that applies theory, principles, data, and other methods in design in order to optimize human well-being and overall system performance [30, 31]. In an ergonomic study, human-centered design always shares an overlapping definition with UCD, but each has its own distinctions, such as those general human factors that are required to design a handle, while specific user factors are crucial for designing a haptic handle for a crane application [32].

2.1.1 UCD

UCD represents a concept, methods, and practices whereby users are the central concern of the design process [33–38]. It is based on an open-systems model and considers the users' and technical subsystem's relationship [39]. In addition, UCD methods guide the focus of the design process onto the user's role in human–machine interaction, which results in dynamics parameters that account for the work, environment, and organization [40]. However, the UCD concept and method do not change the role of user into that of a product designer, nor does the user have any design control authority. Basically, the design of a technical system must involve user participation in the consideration of four factors: functionality, usability, user acceptance, and organizational acceptance [41–43].

The UCD concept is governed by its own principles. Existing scientists have developed similar principles but distinguish attribute positioning according to the application. The nine principles of UCD found in literature research that can be implemented in this study are as follows:

The user(s) as the central focus in the design process. The users, as well as the tasks, should be focused on early in the design process [44]. Besides this, the goals of the users and the design process, the detail task or context of use, and tasks and needs should initially guide the design process by meeting potential users in their work environment [45]. As for design for automation, the tasks should be designed to be best suited to the automation system with a human operator [43]. Therefore, a user-centered attitude should always be established throughout the project team, process, and organization. The degree of UCD knowledge may differ according to the role and project phase, but players in the project must be aware of and committed to the importance of the UCD concept [46].

Active user involvement. In this, users should actively participate, early and continuously throughout the entire development process and throughout the system or product design life cycle. The users in the UCD context are people that represent target user groups for system or product development. Design plans should identify appropriate phases for user participation and specify where, when, and how users should participate. The collection of information from user representatives should be conducted in the working environment in order to inform the design requirements and specifications, and again verify the specifications in the evaluation and testing of the design [40, 43–45, 47, 48].

Empirical measurements. The investigation of users' parameters is conducted using empirical measurement forms, such as questionnaires, usability studies, quantitative performance data, matrices, etc. Basically, the search parameters are related to making the human operator's job an easier, more enjoyable task; making it more satisfying through being a friendly system; extending human power to the greatest possible extent; supporting trust; facilitating the user to gain computer-based information about everything that they might want to know; reducing human error; and keeping response variability to a minimum [43, 44].

Iterative design. The UCD facilitates using an approach that allows continuous iterations with users and incremental deliveries, due to the difficulties in specifically understanding how to design a system or product from the outset. Design solutions can be evaluated by the users before they are made permanent. A proper analysis of the users' needs and the context of use, a design phase, a documented evaluation with concrete suggestions for modifications, and redesign in accordance with the results of the evaluation can all be aided by prototyping. Physical prototypes [49] and virtual prototypes [50–52] should be utilized in order to visualize and evaluate ideas and design solutions in cooperation with the end users [44, 45, 47].

The user as the main determinant. In automation design, it is critical to allocate a human operator in the decision phase and control loop. A human operator is maintained as the final authority and key person for the automation system itself as a precautionary step when considering safety in the working environment [43]. Also, in a complex automation system, the operator is empowered as a supervisor of a subordinate automatic control system, in other words, the human-in-the-loop (HiL) concept should be employed [4, 53].

Evaluate use in context. The design process supposedly produces the best combination of human and system concepts and specifications (i.e., a combination of a human, task, hardware, and software), where the concepts and specifications are evaluated based on usability goals. The goals are specific in aspects that are crucial for usability and cover critical activities as well as the overall use situation. Later in the process, users should perform real tasks with physical or virtual prototypes. The users' behavior, feedback, opinions, and ideas should be observed, recorded, and analyzed [43, 45, 47, 54].

Holistic, practical, explicit, and conscious design. In UCD *holistic* means that all the aspects of design that relate to the user context and influence the future use situation should be developed in parallel [45, 47, 55]. As an example, when developing software to support work tasks, the work organization, work practices, roles, hardware, interactions, manuals, work environments, and so on must be modified. However, the design solutions should be represented in such ways that they can be easily understood by all the people in the design process and show their practicality. The illustrations, diagrams, and terminology (i.e., the prototypes and the simulation used in design) give a concrete understanding and are usable and effective for all the people in a team so that they can fully appreciate the consequences of the design for their future use situation [8, 56]. Additionally, explicit and conscious design activities allow designers to focus on dedicated design activities, which is the final design solution that is the result of professional interaction design as a structured and prioritized activity, rather than the result of somebody doing a bit of generic coding or modeling. In the same way, the UCD process must be customized, specified, adapted, and/or implemented locally in each organization because there is no one-size-fits-all process.

A professional attitude. The design and development process should be conducted by effective multidisciplinary teams, because different aspects and parts of the system design and development process require different sets of skills and expertise [47, 48]. Therefore, a professional attitude is required, as well as professional tools that facilitate the cooperation and efficiency of the design teams.

Usability. There is evidence that usability is a very important principle and a determinant factor in finalizing the design solution (see, e.g., [37, 57–60]) throughout the development life cycle. Thus, the author suggests that the authority to decide on matters affecting the usability of the system and the future use situation should be granted to the usability designer [47, 61].

2.1.2 UXs

The rule of thumb in the UX concept is that the design solution should meet the exact needs of the customer without fuss or bother [62]. An ideal UX exceeds meeting the user’s need; the method supposedly produces positive emotions and an experience design solution [62, 63]. In contrast to a user interface (UI) and usability, there is clear distinction between them, i.e., a UI is a set of software or hardware or a combination of both, such as simulator that provides a driving experience, which is then called a UX, whereas the UI’s quality is determined by a usability parameter, such as being easy to learn, efficient to use, pleasant, etc. [62]. Hence, expertise in multiple disciplines—including engineering, marketing, graphical and industrial design, and interface design—is needed in order to achieve high-quality UX in a design solution.

Three fundamental UX characteristics according to [64] are presented below:

User involvement. In terms of the UCD concept, the position of user involvement in the design process was already discussed in subsection 2.1.1. Another essential aspect is to identify the user's group. Needs could be investigated more efficiently by interviewing lead users [65, 66]. According to these authors, the lead users are those who experience needs months or years ahead of the majority of users and receive continuous benefits from product or system innovations.

The user interacts with the product, system, or interface. Basically, a UI relationship is developed based on several or all five of the following lenses: the mind, proxemics, artifacts, the social lens, and the ecological lens [67]. In this study, the Fitts list [44, 67] answers the question of how to integrate human intelligence with machine intelligence. Figure 1 illustrates the correlations between the five lenses and the Fitts list in order to establish the user interaction relationship in this study.

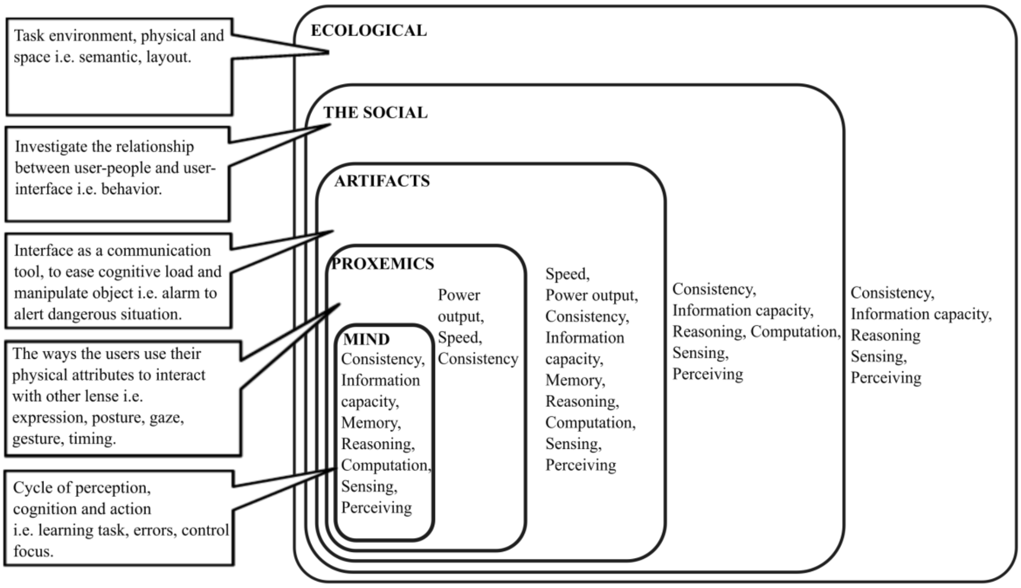


Figure 1 Correlations between the five lenses and the Fitts list

The UX is observable and measurable by translating the experiences into metrics [64, 68]. Five basic types of performance metrics are listed in Table 1 [68].

Table 1 UX metrics: their definition and units

UX metrics	Definition	Unit
Task success/failure	User effectiveness in completing a given set of tasks	The number of successes/failures Levels of success/failure
Time spent on a task	The time taken to complete a task or a set of tasks	Time
Error	Mistakes made when completing a given set of tasks	The number of errors
Efficiency	The amount of effort a user contributes to completing a given set of tasks	Numbers Percentage
Learnability	Performance improves or fails to improve over time	Percentage

2.2 Ethnography

Ethnography is a tool that is used to investigate the knowledge of sociology in empirical detail. Ethnography's accountabilities, needs, results, and use in a design application are distinctive compared to ethnography's application in social science [69]. Ethnomethodology in design [70–72] focuses on three fundamental principles: the work, a naturally accountable setting, and reflexivity [69]. Firstly, the work is conducted in a user setting that is involved in completing the normal work. The work requires practical effort from the user in order to be completed, as well as other people's involvement no matter how familiar the work is to the user. Secondly, the setting of the work is naturally accountable so that the user can see the work that is going on around them and knows what it is that they and the other parties in the work are doing. The last principle is reflexivity, meaning the need to investigate the work according to the user setting rather than the designer setting, and to develop a distinctive analytic orientation that enables the empirical discovery of the work involved in assembling and accomplishing naturally occurring activities. In this study, ethnomethodology is important in uncovering the UI interaction in relation to the user's culture and behavior. The methods used in ethnomethodology are generally similar to UCD methods (i.e., textual, observational, audio-visual, interview, and digital methods). Therefore, these similar methods could be used to obtain multiple objectives in this study.

2.3 Conjoint analysis

Paul Green and V. Srinivasan introduced conjoint analysis in 1978 to determine how people value different features, i.e., attributes, aspects, characteristics, factors of a product or service in marketing field [73]. Conjoint analysis helps scientists and businesspeople to search for and prioritize the important features to end users in a specific application, such as the main factors that influence buying decisions among teenagers. Often choices are made by trading off perceived advantages against disadvantages. For example, low price and high quality will most likely be preferred to high price and low quality, but other characteristics like color and size may play a role too. With conjoint analysis, a limited number of important characteristics of a product, like a gantry crane, are selected by the investigator, and each characteristic is given a level, e.g., from cheap to very expensive. Then, orthogonal modeling of the characteristics is performed [74]. The analysis assumes that the utility for a product; U can be expressed as a sum of utilities for its attributes; $u_1(QA_1) + u_2(QA_2) + \ldots\ldots$ and utilities can be measured by a customer's overall evaluation of product; $u_i(QA_i)$. Each quality attribute has a different functional form to overall utility [75].

$$U = u_1(QA_1) + u_2(QA_2) + \ldots\ldots = \sum_{i \in \text{attributes}} u_i(QA_i) \qquad (1)$$

Conjoint analysis is regularly applied in marketing research and is available in modern statistical software, but it is rarely used in engineering applications. It can provide a complementary method for measuring user utility in a quantitative manner and can help the researcher to measure user utility quantitatively and objectively through a well-defined process. Since conjoint analysis delivers suitable design sets, users only need to answer and specify their preferences through ranking or comparisons without understand the whole measurement process, and then the defined conjoint analysis process will reveal the hidden user preferences.

2.4 Engineering design

The parametric engineering principles, methods, and approaches used in engineering design i.e., design specifications [66], quality function deployment [QFD] [66, 76], the technical model [66], and morphology chart methods [66, 76] are emphasized in this study in order to analyze the UX results and set more understandable criteria and measurable parameters according to engineering definitions.

Design specifications are the set of attributes that consist of a metric and a value for each attribute. These attributes are produced from the study of UXs and needs interpretation. Four processes were established by Karl T. Ulrich [66] in order to develop the design specifications: 1) prepare the metrics list, 2) collect and record competitive design benchmarking data, 3) propose ideal and marginally possible values for the metrics, and 4) reflect on the results and the process.

Then, the QFD presents the information in the design specifications in the form of a graphical illustration [77]. QFD illustrates the relationship between UXs and design specifications by using matrixes. It also keeps track of the relationship between the metrics and helps the designer make trade-offs between the metrics [78].

A morphology chart [79] is a simple grid of empty cells, filled with a metric list in the left-hand column and the methods for achieving the metrics in each row. The methods suggested in the morphology chart will be the available and possible solution forms for the metrics and especially for the subjective solutions (i.e., geometry, list, types, etc.) The information type used for describing the methods could be a simple written or graphic mode. The chart offers a wide range of solution combinations presented in each row. It is important to note that the list of methods is suggested to be limited to five options [79].

2.5 Haptic control for remote operating

Touch is a fundamental interaction attribute between a human and their environment and also in their interpersonal communication [80]. The sense of touch is called *haptic feedback* or *tactile feedback* [81, 82]. Haptic feedback provides intuitive control through sensory feedback in a multimodal environment [83]. Haptic feedback is important in automation as a sense of touch does not automatically give an operator complete control over the machine, assuming that the operator is more intelligent than the actuators of the haptic device [84]. Also, it is still preferable to give the power to make final decisions to a human operator in order to ensure safety [85]. This is because the standards for control systems' safety of working machinery are at a significantly higher level if the machinery is designed to operate autonomously [86]. Therefore, vibration and force parameters are proposed in this study as a solution for the lack of direct motion feeling while operating and handling an ORV remotely.

The application of haptic technology in ORV design has led to ergonomic UIs and machinery that can be operated with a small amount of effort. In a common application of a control system, haptic feedback comprises vibration and force feedback. The haptic sensations are provided for the operator through an operating interface, such as control levers or joysticks. Haptic feedback is important for the remote-operating operator as it enables them to feel as if they are directly manipulating and touching the remote environment, which is called *telepresence* [87]. Designing the haptic feedback in a remote-control system based on the inertia of the controlled machine can be used to achieve telepresence [21]. However, a haptic interface can be useful in order to help the operators complete the operation using minimal effort if they are present and active in the working environment [88].

Previous studies on haptic-controlled crane applications, such as Villaverde, Lee, Chi, and Sanfilippo [21, 89–91], have shown that sway amplitude and the time required for stabilizing the load can be reduced with force feedback. In addition, when controlling large cranes, a relatively small oscillation can be difficult to distinguish, but through haptic feedback, small changes can be clearly informed to operators.

2.4.1 Force

A signal can be generated by a teleoperator controller taking the form of force and torque vectors, which result from the handgrip force felt by a human operator [92]. These vectors are expressed in a coordinate frame parallel to a local frame fixed to the handgrip.

According to Waters [93] (and again used in [94]), the maximum allowable stress or force for a human hand 1) should not generally exceed one-third of their isometric strength on a sustained basis in task performance, 2) should avoid overloading of muscles (in order to minimize fatigue), 3) should be of a dynamic force that is <30% of the maximum force that the muscle can exert, with up to 50% being acceptable for up to 5 min, and 4) a static muscular load that is kept <15% of the maximum force that the muscle can exert. General guidelines suggest that hand forces should not exceed 45 Newton [94].

A study was conducted by Swanson [95] regarding the handgrip strength of normal people with and without a support (i.e., with the arm or elbow resting on a table or held close to the body). The participants were normal individuals from the West in the range of 17–60 years of age. It was found that handgrip strength was weaker when the extremity was supported compared to when it was unsupported. On average, the load of supported extremities for the male group was 44.7 kg for the dominant hand and 41.7 kg for non-dominant hand. The female group showed an average load of 22.3 kg and 20.1 kg for each hand. Another similar study was also conducted among Asian participants by Lam [96], and the results are presented in Table 2.

Table 2 Handgrip strength data by Lam

Gender group	**Age (years)**	**Average handgrip strength (kg)**	
		Dominant hand	**Non-dominant hand**
Male	60–64	39.5	36.6
	65–70	34.2	31.0
Female	60–64	26.0	23.9
	65–70	22.3	20.4

2.6 Usability testing

According to Barnum [97], “big” usability encompasses the methods, techniques, and tools that support the understanding of UXs and the process of creating usable, useful, and desirable products, while little usability is specific to observing and learning activities in relation to the product usage, its users, and their real and meaningful interactions.

The guidelines for conducting cross-cultural usability testing [98], as illustrated in Figure 2, are significant in this study as multicultural users were involved in this study.

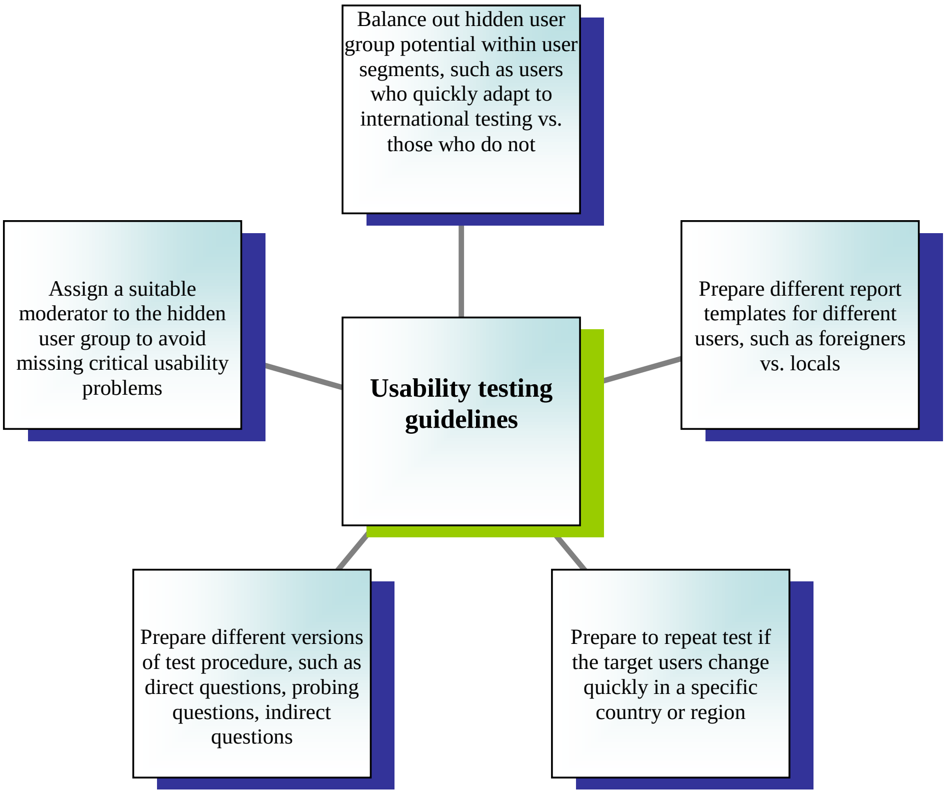


Figure 2 Guidelines by Barnum during cross-cultural usability testing

A set of usability goals, as shown in Table 3, set according to ISO 9241-11 [47, 99, 100] and Heuristics principles [101], were applied in usability testing as measurable parameters for further analysis and for the evaluation process.

Table 3 Usability goals according to ISO 9241-11

Usability goals	Measurable parameter
Effectiveness	The number of operating cycles in 10 minutes of operation
Efficiency	The period of effort to control and handle a crane spreader approaching a container task
Satisfaction	The positive perceptions and experiences encountered while interacting with the haptic feedback and haptic joystick interface

Remote or moderate usability testing is not new in the UCD process [102]. This method is practiced with the observer in one location and the user, with an interface or prototype, in another. The method comes down to two main concepts: moderated and unmoderated testing. *Moderated testing* means having a moderator remotely present during the testing, while *unmoderated testing* does not use a moderator or observers, or any of the other techniques used in moderated testing. The online meeting application, such as WebEx and Skype, facilitates the practitioner conducting a moderate remote test using the same techniques that are used in field testing, such as the think-aloud technique, recording the user’s actions and behavior, and interviewing the user.

3 Methodology

3.1 Introduction

Figure 3 illustrates the main methodology framework used in this study. It is produced from three design approaches, which are the UCD approach, the engineering design approach, and user testing. Two methods were developed based on UCD, namely the investigation into UX goals method and analysis and evaluation methods on UX goals. The methods for listing design metrics development ware established based on the engineering design approach. Finally, four methods established based on the user testing approach, i.e., haptic feedback testing, statistical analysis on haptic feedback hypotheses, usability testing and analysis, and evaluation of haptic usability. The equipment and tools, methodology flow and the expected results are organized and presented in Figure 4. The methodology establishments for this study are further elaborated in subsections 3.2 to 3.5 in this chapter.

Figure 3 The main methodology framework

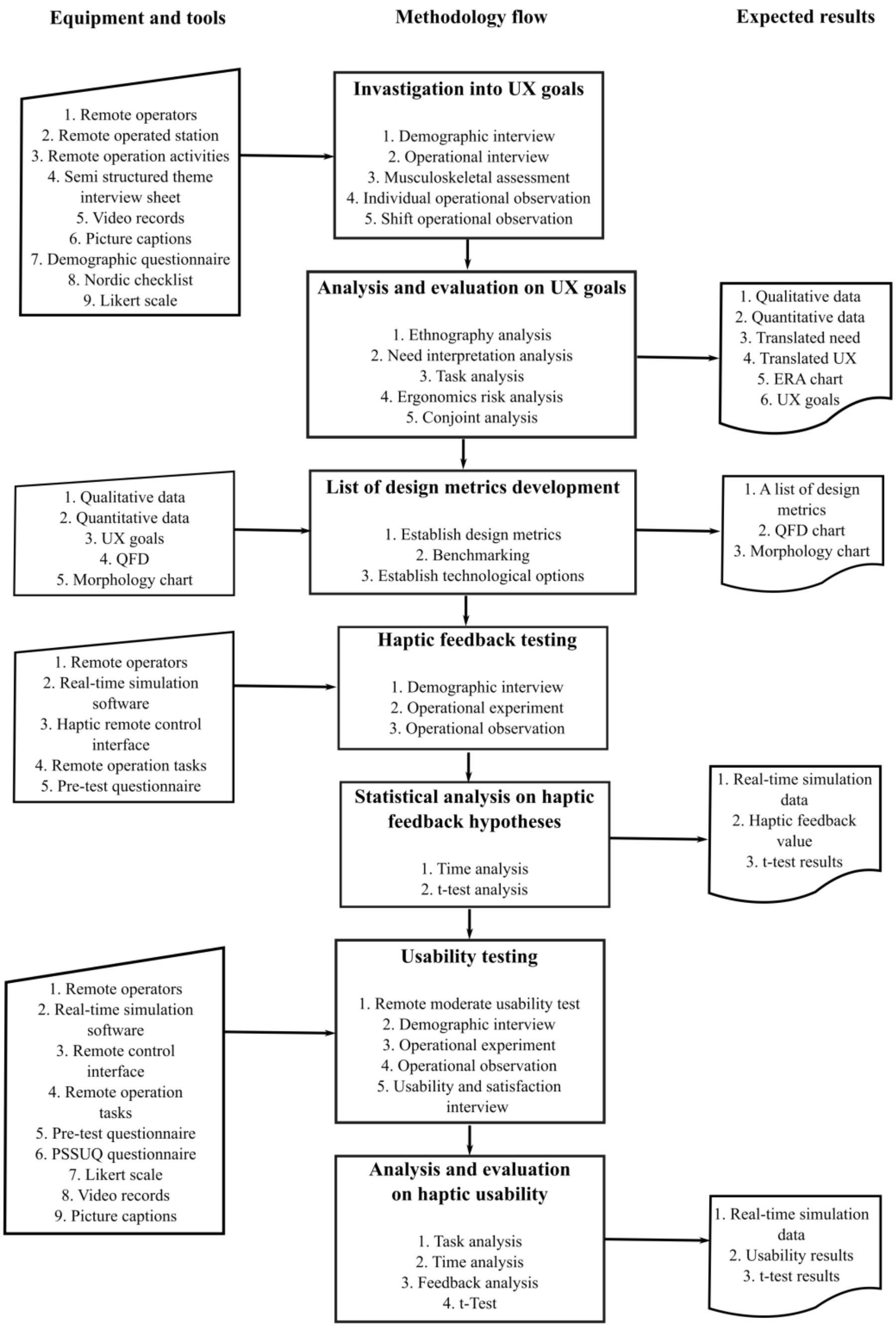


Figure 3 The methodology flow in this study

3.2 UX goals investigation in remote-control interface of an ORV

3.2.1 Objectives

This chapter describes a study that was conducted to achieve the first objectives, which were to obtain UX data about a remote control and the handling interface, and to propose the related UX goals. This study concentrates on the issue of the lack of direct motion feeling during the remote operating and handling of a container crane. The usage of the ROS in the handling and controlling of the crane movements is possibly a factor that leads to the loss of the physical operation’s sense and the feelings that would have been gained via sounds and vibrations from working in a vehicle. Therefore, an investigation was conducted to explore and verify the issue.

3.2.2 Methodology

Thirteen remote operators from two international container terminals located in Indonesia participated on a voluntary basis. The participants were four female and nine male operators with an average age of 28.5 years. Six of the operators had an average of 2.5 years of experience in conducting an automated stacking crane (ASC) remotely while the other seven had an average of 4.2 years of manual operation experience, and an average of three months’ experience in remote automated rubber-tired gantry (A-RTG) operation at the time this research was conducted. All the operators communicated in their local language, but they understood and used English as a working instruction language.

Figure 5, parts (a) and (b), show the types of crane that were controlled by the ROS. Figure 5 (a) illustrates the ASC while Figure 5 (b) illustrates the A-RTG used for loading, unloading, and stacking the containers in the terminals. The ASC is a gantry that is mounted and moves on a rail. On the other hand, the A-RTG is a gantry that moves freely on rubber tires. The spreader system for both cranes functions as the container holder during loading, unloading, and stacking activities. The spreader unloads the container automatically but loads and stacks the container on the truck manually by remote operator due to the safety factor (e.g., to reduce the risk of collisions).

(a)

(b)

Figure 4 (a) An automated stacking crane (ASC) and (b) An automated rubber-tired gantry (A-RTG)

Both an ASC and A-RTG are operated remotely using the ROS shown in Figure 6. All the operators used the same ROS, consisting of a display or monitor screen for viewing the loading and unloading operation in remote terminal blocks and a graphical user interface (GUI). The headphone and microphone unit functioned as a communication interface between the remote operator and the people in the operation blocks, such as the truck driver. However, the truck driver only received the instructions from the operators–they could not respond verbally. The control panel on the ROS functioned as an information feedback and operation controller that the operators were able to change between automatic operation and manual operation. Finally, a pair of joysticks on the ROS helped the operator to control and handle the crane in manual mode for safety reasons, for instance, using manual mode during container loading and unloading operations in the terminal blocks.

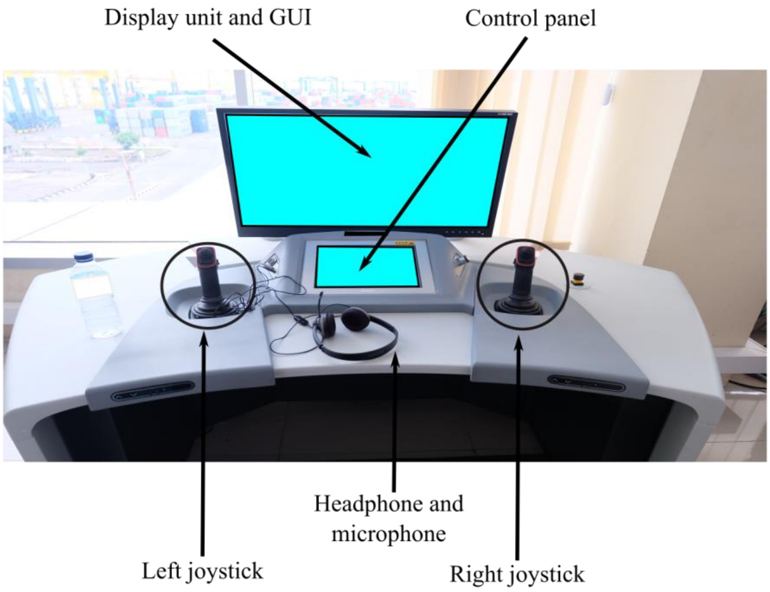


Figure 5 The ROS, with its main interfaces, which is used for operating the ASC and A-RTG remotely

A brief explanation was given to the participants about the objectives of the study before the investigation started. The instructions and requirements of the tasks to be undertaken during the study were also explained to the participants. Next, a demographic interview [98], musculoskeletal assessment [103], operational interview [66] and operational observations [66] were conducted, each of which took about an hour per participant. The interview sessions involved tools such as a semi-structured themed interview sheet, [104], UX questionnaire as shown in Appendix A, and the Nordic checklist as referred to in [105]. A five-point Likert scale [106] was used in the semi-structured interviews with point one defined as *strongly agree*, point two as *agree*, point three as *not sure*, point four as *disagree*, and point five as *strongly disagree*. After that, all the operators in every work shift were instructed to conduct the normal and daily operation routine using the ROS, while a video camera recorded their activities for one hour. The observed tasks included unloading a container from a block, loading the container onto trucks, and stacking the container in the terminal blocks.

Ethnography analysis [41], ergonomics risk analysis (ERA) [107], need interpretation analysis [26, 108], conjoint analysis [7, 109], and task analysis [110] were conducted in order to establish the UX goals in the form of a collective set of needs for lack of direct motion feeling improvement through the joystick interface design.

3.3 List of design metrics development methods for UX goal communication options and problem detection

3.3.1 Objective

The objective of this study is to establish methods for developing a list of design metrics based on UX goals, and to propose the design specifications for the joystick interface of a remote-operated container crane (ROCC). A list of design metrics is required in this study in order to translate the UX goals, UXs and user needs into a set of possible, precise, and measurable technical parameters that would lead to usability and the satisfaction of the associated customer experience and needs. In this study, the development of the list of design metrics is focused on the first and second hierarchy of UX goals presented in chapter three: communication options and problem detection.

3.3.2 Methodology

Design specifications [67, 83] consist of the combination of functional requirements and customer requirements that are called *metrics* [66]. Initially, the customer requirements were obtained from the operator experiences and their suggestions, which had been coded into UX goals. A list of metrics was developed by interpreting the UXs in the design parameters [111]. Five guidelines from Ulrich [66] were followed during the interpretation of the UXs. The guidelines were important to produce effective translation of UXs and to ensure the consistency of phrasing and style while translating the UXs. The first guideline that was used was translating the UXs into what their experiences are, rather than their solution concepts or implementation approach. The second guideline was translating the UXs at the same level of information detail as raw data, i.e., no less and no over-translation. The third guideline was using positive phrasing in translation of the UXs because it was easier to transform them into measurable metrics. The fourth guideline was translating the UXs as attributes of the future solution to ensure consistency and help subsequent translation into technical specification. Finally, the fifth guideline was avoiding the words *must* and *should*, as they represent a level of importance rating. However, the levels of importance for the UXs were not assessed in this process, so the words were not used while translating the UXs.

Next, the benchmarking activities was conducted in order to compare the measurable target values of the UX metrics [66]. The metrics and their measurable values were obtained in relation to the UX goal of *communication option* and *problem detection.* Then, a QFD [112, 113] was established to understand the relationship between UXs, the metrics, and the target values. Finally, a morphology chart [114, 115] was established to understand the technological choices available for meeting the solution requirements for the communication options and problem detection.

3.4 Assessing the effects of haptic feedback control in an ORV remote control operation

3.4.1 Objectives

This chapter studies haptic force as one of the technological solutions for the output metric of the UX, the ability to communicate with the operator and haptic force implications for joystick control equipment, and force as a safety indicator in the UX that is used for problem detection. The objectives of this study are to investigate haptic technology in relation to the users' age and gender, and in relation to the effect of taking a break between the given tasks. This chapter also investigates three hypotheses:

1) H_0: There is no significant effect of haptics on the controllability of an ORV between the age groups: feedback from those <30 years old = feedback from those >30 years old.
   H_1: There is a significant effect of haptics on the controllability of an ORV between the age groups: feedback from those <30 years old ≠ feedback from those >30 years old.

2) H_0: There is no significant effect of haptics on the controllability of an ORV between genders: feedback from males = feedback from females.
   H_1: There is a significant effect of haptics on the controllability of an ORV between genders: feedback from males ≠ feedback from females.

3) H_0: There is no significant effects of haptics on the controllability of an ORV before and after rest: feedback before rest = feedback after rest.
   H_1: There is a significant effect of haptics on the controllability of an ORV before and after rest: feedback before rest ≠ feedback after rest.

3.4.2 Methodology

Eight participants were involved in the haptic joystick operating test on a voluntary basis. Two age groups were identified: those below 30 years old and those above 30 years old (with means of 26.5 and 45.7 years old respectively).

The experiment's hardware setup consisted of Mevea gantry crane simulation software and a haptic joystick system, as shown in Figure 7. The Mevea real-time simulation illustrated the spreader's movement simulation according to the task operated by the user. The spreader's downward movement was controlled automatically by programming, while the upward movement was controlled by the operator. This movements setup was simulated according to real remote-crane operation in the existing work environment. The haptic joystick system's hardware consisted of a joystick mounted on haptic hardware and a laptop as the simulator, as shown in Figure 7.

The participants were first briefed on the purpose of the operation task and the testing hardware and software setup upon arrival. A pre-test questionnaire [116] was administered to obtain the participants' demographic information. The participants were seated in front of an automated rubber-tired gantry (A-RTG) real-time simulator, as shown in Figure 7. Then the participants were instructed to complete the operation task while the observer conducted the remote haptic feedback testing [117] using an online meeting application. The participants used the haptic joystick to control the crane spreader's approach speed to the containers stacked for an unloading operation. The haptic feedback gave force to the participants' handgrip as a signal to slow down their approach to the container. The first test was conducted for 10 minutes of operation before the participants were given a one-hour break. Then, the second test was conducted with a similar task lasting another 10 minutes. The experiment took approximately 1 hour 30 minutes per participant to complete.

The data from the simulation programming was analyzed using the time analysis technique [118] to obtain the results. Statistical analysis, such as a statistical *t*-test analysis [119], was used to validate the significant value of three hypotheses relating to age, gender, and the rest effect factor in order to reject the null hypotheses or vice versa.

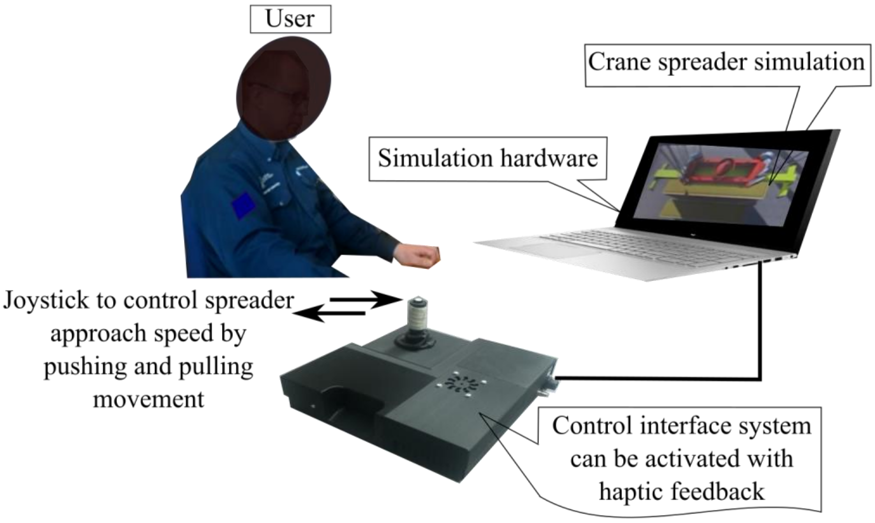


Figure 6 The user, hardware and Mevea real-time simulation software testing setup

3.5 Usability testing of haptic feedback interface of remote-operated ORV

3.5.1 Objectives

This section studies the usability of haptic feedback and a haptic joystick interface for the ROCC application based on ISO 9241-11. Previously, the haptic joystick system was developed to solve the lack of direct motion feeling among operators in remote container crane control and handling operation [4, 10, 16, 18, 28, 120]. This study focuses more on UXs and interaction relating to the haptic feedback and the haptic joystick (i.e., its effectiveness, efficiency, and user satisfaction) rather than on hardware and software development. This study contributes to the usability attributes based on the end user's experience in designing a similar haptic interface for the remote control and handling of an ORV. This chapter investigates the two following hypotheses:

1) H_0: There is no significant operation cycle difference between haptic operation and normal operation: Haptic operation cycle (C_{haptic}) = Normal operation cycle (C_{normal})
H_1: There is a significant operation cycle difference between haptic operation and normal operation: Haptic operation cycle (C_{haptic}) ≠ (C_{normal})
2) H_0: There is no significant task time difference between haptic operation and normal operation: Haptic operation time (t_{haptic}) = Normal operation time (t_{normal})
H_1: There is a significant task time difference between haptic operation and normal operation: Haptic operation time (t_{haptic}) ≠ Normal operation time (t_{normal})

3.5.2 Methodology

Eight participants were involved in the usability testing. The participants were selected equally in terms of their gender, and the mean age was 36.1 years old. All the participants involved in the testing took part on a voluntary basis.

In this study, a haptic joystick system was developed to solve the lack of direct motion feeling among operators in remote container crane control and handling operation [3]. The haptic joystick system consists of a joystick that stands on a base and gives real-time input regarding the shredder operation and movement, haptic hardware, a Mevea simulator, and a laptop as the simulation hardware, as shown in Figure 7. The Mevea simulator simulated the real-time operation environment by combining the virtual and real world and giving a realistic feel [121]. Mevea software was used because it was developed for the real-time modeling and simulation of ORVs, it has a versatile real-time interface that can be connected to multiple types of external hardware, and it provided the GUI for complex modeling purposes [4].

The participants were first briefed on the purpose of the study, the operation task, and the testing simulator upon arrival. A pre-test questionnaire was administered [116] to obtain the participants' demographic information. The participants were seated in front of a real-time RTG Mevea simulator setup. Then, the participants were instructed to complete the operation task while the observer conducted the remote moderated usability testing [117] using an online meeting application. The test was conducted in two modes: 1) using a haptic joystick for ten minutes of operation, and 2) using a normal joystick for ten minutes of operation. The participants controlled the crane spreader's speed as it approached the containers stacked for the unloading operation by pushing and pulling the joystick. In the first mode test, if the spreader's approach speed was too high near the container, the haptic feedback gave a jolt to the participants' handgrip as a signal to slow down (by pulling back on the joystick), while in the second mode test, there was no haptic feedback given to the participants to warn them about controlling the spreader's approaching speed because the haptic system was deactivated. A set of videos and captions were captured during the tests for better observation [116]. The test session was completed by conducting an interview with each participant using a post-study system usability questionnaire (PSSUQ) [122], as presented in Appendix B, to investigate the usability components based on the participants' perceptions and experiences. A seven-point Likert scale of response choices was used in the PSSUQ form [123] in which 1 was *strongly agree* or *excellent satisfaction* and 7 was *strongly disagree* or *the worst level of satisfaction*. Overall, the experiment took about one hour per participant to complete. The videos, pictures, and responses from the pre-test and PSSUQ forms were analyzed to obtain the usability results. Finally, statistical analysis using a *t*-test was conducted to test the hypotheses.

4 Results and discussion

4.1 UX goals for control interface design of remote-operated ORV

4.1.1 End users' positive experiences

Figure 8 shows the results relating to positive experiences based on operational interviews with the ROS operators. The results show that *an acceptable safety risk* was the most positive experience, which was selected seven times, followed by *good ergonomics*, which was selected five times, and *low mental workload*, which was selected four times. The other positive experiences mentioned by operators were *minimal manpower requirements*, *increased time performance*, *reduced operation task complexity*, *less frequent maintenance,* and *easy handling,* with the frequency of option selections ranging from three to one.

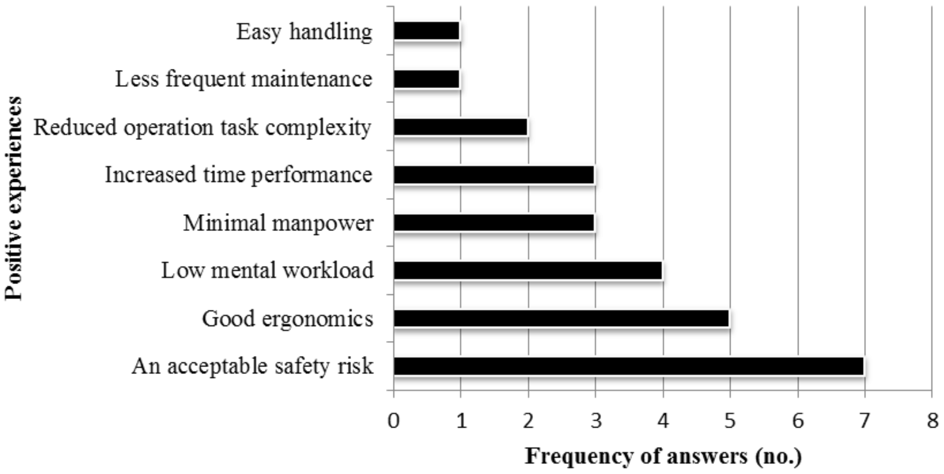


Figure 7 The frequency of selection for options regarding the positive operator experiences of using the existing ROS

An acceptable safety risk experience according to the operators relates to less occupational risk to the operator such as forceful exertion, awkward posture, vibration, and noise. In addition, operators claimed that ROS eliminates cabin shaking and protects operators from rain and strong winds. The existing ROS design equipped with safety sensors, e.g., collision sensors, also increases confidence levels among operators during operation with ROS. The operators also experience minimal accidents and feel that they are a safe distance from the machines and other people in the terminal area, compared to when operating the cranes manually in the working cabin. Figure 9 illustrates the positive ROS criteria that were classified as acceptable safety risks by operators during the interviews.

Figure 8 Positive ROS criteria classified as acceptable safety risks

The experience of *good ergonomics* was coded for responses which referred to the existing ROS helping body posture improvement. The other related response was that operators were able to visualize the container from a comfortable sitting position compared to having to bow their backs to see the container under the working cabin during manual operation. The new position automatically reduces the risk of back pain among operators. The existing ROS also allows operators to change their working position from sitting to standing and vice versa by adjusting the workstation height. Figure 10 shows the good ergonomics of the existing ROS.

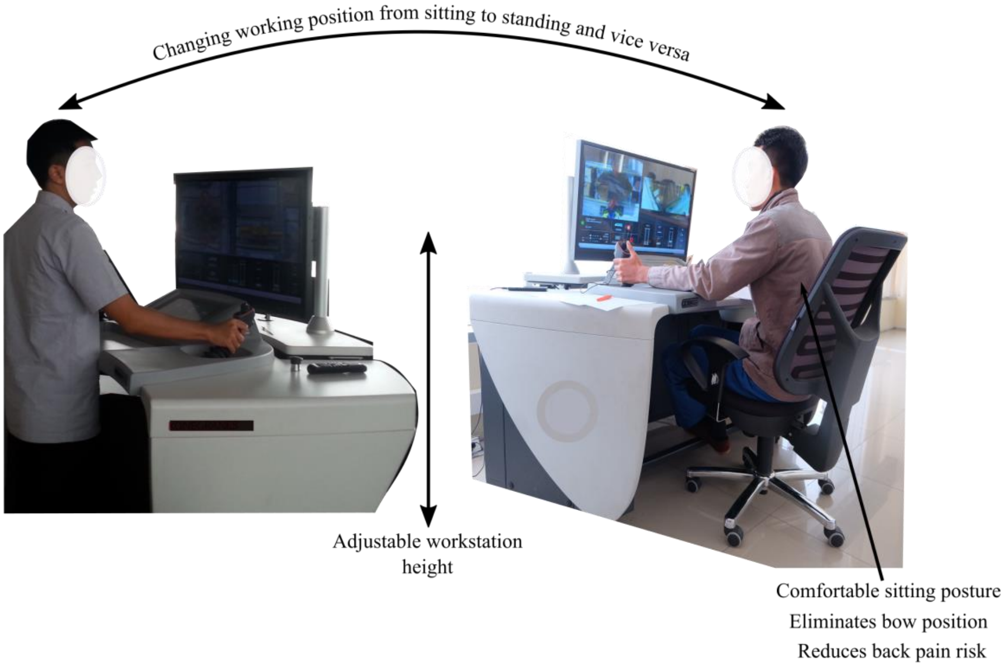


Figure 9 Ergonomics sitting of existing ROS

Under the *low mental workload* experience coding, the answers are related to existing ROS that provides a relaxed working experience, i.e., the workstation is in comfortable office compared to a small cabin; and the ROS reduces fatigue, which helps improve mental workload issues such as easily tiring due to focusing on controlling the crane manually for a long time.

The *minimal manpower* experience coding classifies the responses related to the minimum number of operators required for ROS for handling and controlling crane tasks compared to cabin operation. An operator could handle and control many cranes continuously without changing workstations. In addition, the ROS allows the operator to handled and control multiple types of cranes in different terminal blocks by using a single workstation.

The increased time performance experience coding groups responses related to the handling, controlling, and loading times becoming faster by using ROS. The responses related to eliminating the climbing task experience and closed-circuit television helping operators visualize the different working environment angles without being present in the terminal blocks are classified under the *reduce operation task complexity* code. The code of *less frequent maintenance* refers to ROS interface durability, which relates to the fact that frequency of damage is low, e.g., only one pair of joysticks was changed in a year of usage. Finally, the *easy handling* code classifies the easier reorganizing and restacking of the containers using ROS compared to manual operation.

4.1.2 End users’ negative experiences

Figure 11 illustrates the results based on an operational interview regarding the negative experiences of using the existing ROS. *Time delays* had the highest frequency of selection regarding negative experiences, receiving nine responses, followed by *problem detection*, which received eight responses, and *communication options*, which received six responses. The other negative experiences were *visual limitations, handling smoothness*, *ergonomics, working sensation,* and *control difficulties,* which all had a frequency of selection ranging from two to four.

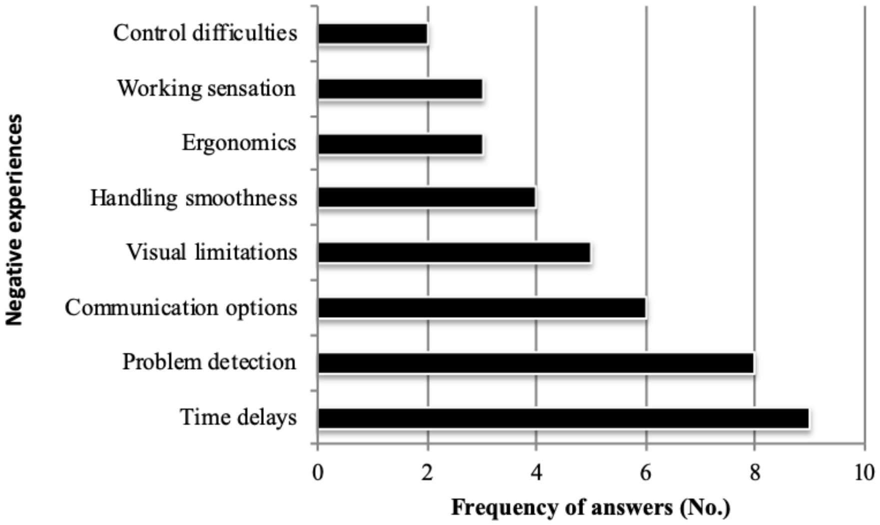


Figure 10 The frequency of answers regarding negative operator experiences of using the existing ROS

The *time delay* coding groups the responses related to time delays in container crane remote operation, such as the inability to control the joystick in manual mode when the spreader in the terminal block is automatically locked. As a result, the operator paused the operation until the maintenance worker unlocked the spreader manually. In addition, the time lag that occurred between real operation and the visualized operation influenced the operator’s efficiency and decision-making while handling the cranes remotely. A time lag also occurs during joystick handling, i.e., the spreader moved slowly, even when applying maximum pull on the operation joystick. This meant that the operator needed to activate the camera transfer button to accelerate the spreader speed. Joystick weight was named as a factor that influences the push-pull movement, which was heavier compared to the joystick used in cabin operations.

The *problem detection* coding classifies feedback on difficulties in detecting problems and danger while moving the containers in the terminal block. Difficulties with visualizing the operation in the terminal frequently occur during bad weather, such as heavy rain due to the camera view being obscured by water droplets, resulting in bad visuals through monitors, as illustrated in Figure 12. In addition, the existing control interface (the joystick) did not provide any signal to alert the problem or danger situation to the operator: for example, the spreader cable suddenly stopped, the spreader lifted up the container while it was still attached to the truck, the spreader tilted and collided with a container and a hydraulic cable truck. Sometimes, the sensor cannot detect the truck movement in a terminal block, which led to problems for the operator because the system declared it was a fault operation that required the operator to take some time to investigate the cause. The operators claimed that the fault operation disturbed their focus on the operation because they needed to move from their ROS to another control station to identify the fault status, as their existing ROS was not equipped with any interface that alerted them to the fault operation condition.

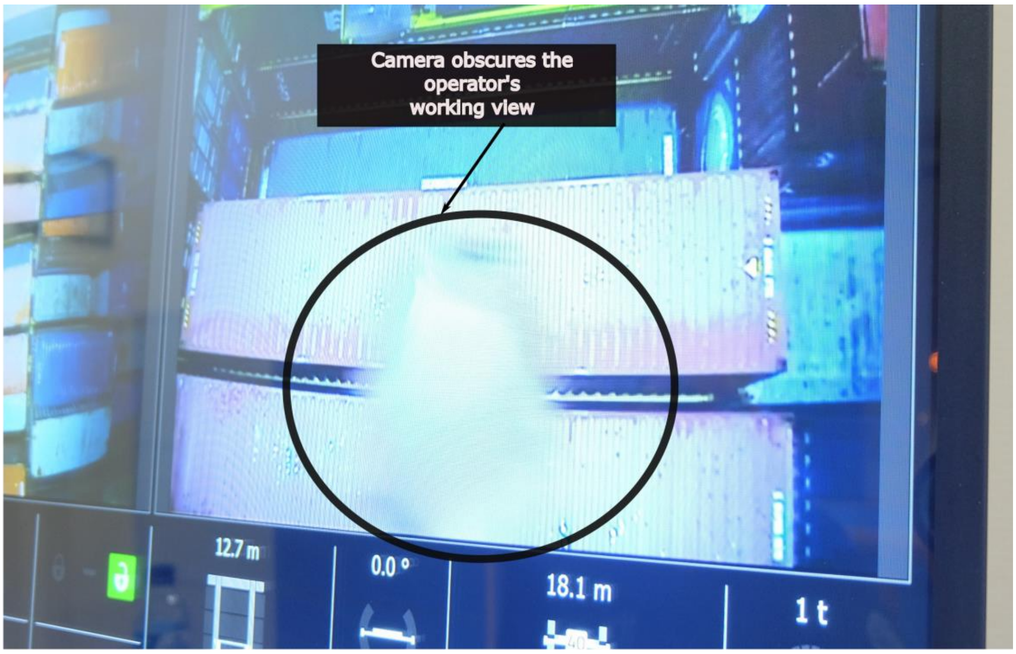


Figure 11 Bad visual from ROS monitor due to water droplets on camera during heavy rain

The *communication options* coding categorizes responses related to the limited options of communication tools that can be used during emergency situations, such as tilting spreader, collision, poor working views, and many more. The main communication interface was monitors and small microphones, as illustrated in Figure 13. All operation information can be visualized on the screens, which the operator has to operate blind when the screens are experiencing problems. The microphone can only be used to give instructions to the truck drivers. The interface that the operator uses to receive instructions from truck drivers was not equipped with the existing ROS. As a result, the truck driver gave hand signals to the remote operator through closed-circuit camera when necessary. Finally, the operator experienced limited ways to communicate with people in the terminal blocks without voice feedback from the ground.

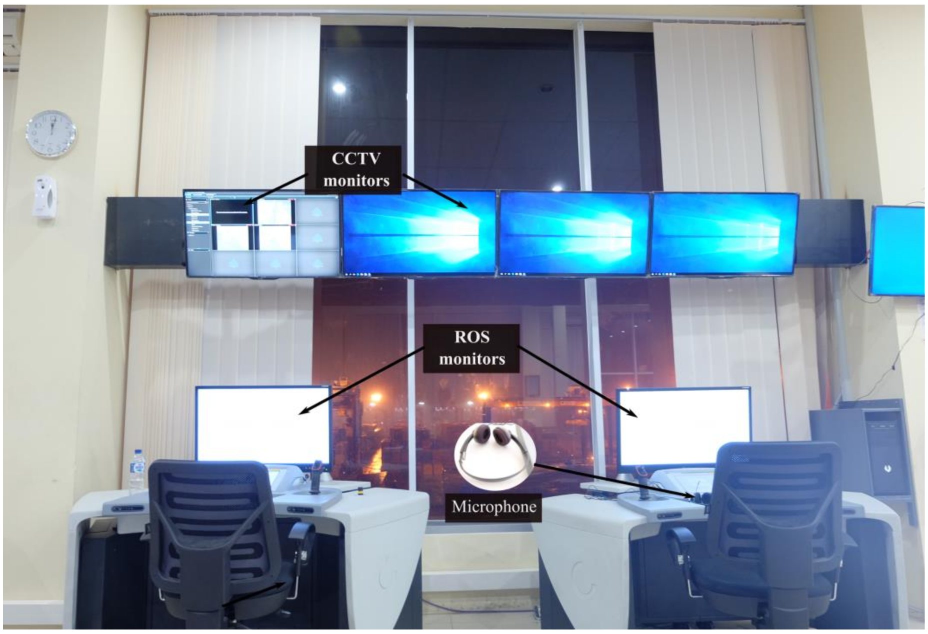


Figure 12 Main communication interfaces equipped with ROS

The *visual limitations* coding groups responses related to the weaknesses of closed circuit camera, which led to poor visual experiences for the operators due to shadows and glare from terminal lights during the dawn, night, and late evening shifts. In addition, the light reflections in the terminal block during night-time produced an over-bright visual on the operators' ROS monitors, which made it difficult for the operator to recognize the objects in the terminal block. However, there were difficulties viewing the spreader locking area during locking and unlocking of the containers during the night shift because of lack of lights, so the camera itself was of no help to the operator when having to view the operation in the dark. The same problem occurred during late evening operation, but the cause was related to shadows that covered the visuals from the camera. Finally, the operators experienced shaking visuals from the spreader camera, for example, due to the spreader's movements. Figure 14 shows examples of the visual limitations in the existing remote operation.

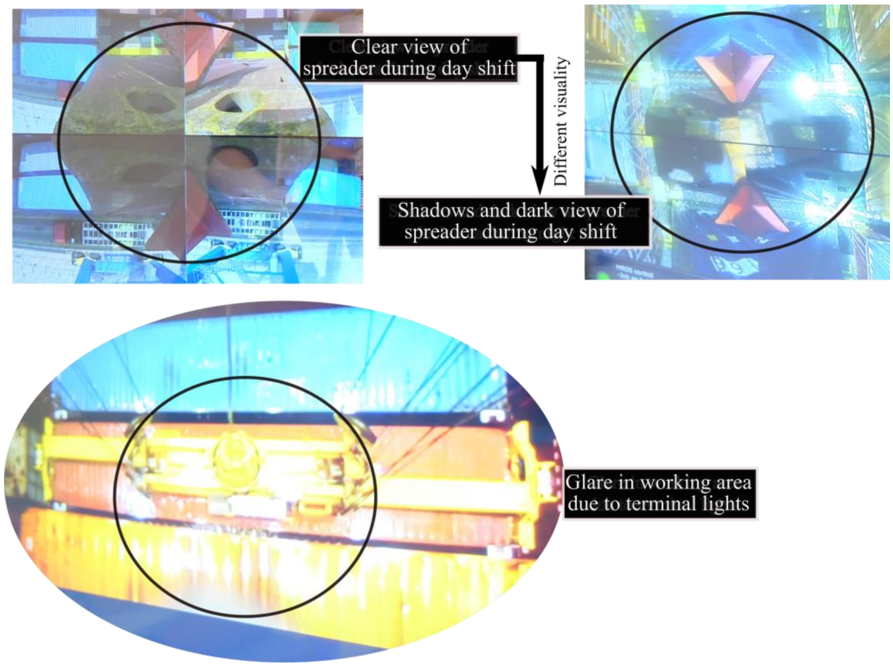


Figure 13 Examples of visual limitations in remote operation

The *handling smoothness* coding group responses related to the automatic control system for spreader movement that was easily halted in the middle of operation. The automatic control smoothness was interrupted due to bad weather, e.g., strong winds and heavy rain, or the spreader suddenly stopped moving with no explanation. The joystick's heaviness also influenced the handling smoothness compared to the joystick used in a cabin operation.

The *ergonomics* coding classifies experiences of eye strain due to focusing on the ROS monitor to view the operation and working views clearly during the work shift. The operator also experienced pains at hand and arm area after long working hours due to handling and controlling the operation tasks using the joystick.

The *working sensation* coding categorizes the experiences of loss of working sensation due to remote operation, i.e., specific sounds and vibrations usually gave the operator some insight about what was happening during operation. Without the sounds and vibrations from the working machine, the operator felt too calm and lost the feeling of real work.

Finally, the *control difficulties* coding summarizes the responses related to the difficulty in changing the spreader movement when there was an operational fault. The operator had to pause the operation until a programmer or maintenance people had dealt with the related problem. Sometimes, the operator experienced loading the container on the truck in the wrong door position and the task couldn't be repeated in order to change the position.

4.1.3 End users' suggestions

Figure 15 shows the results of the users' suggestions based on their experiences of using the existing ROS. Seven responses from participants suggested improving the communication options, while six responses suggested ergonomic enhancements. The other suggestions are related to problem detection, improving the traction, time delays, and having a tough interface for repetitive usage; the range of frequency of these responses ranged from one to two.

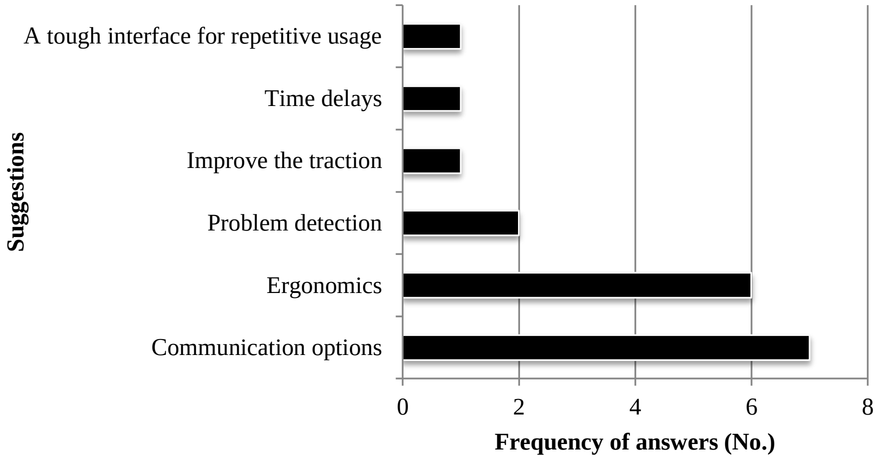


Figure 14 The frequency of end-user's suggestions based on their experiences

The *communication options* coding categorizes suggestions from the operators relating to options that would help them to communicate with other people and receive information from the operation system. The suggestions were an interface to speak with truck drivers in the terminal, add a signal such as 'tik' sound to attract attention, and add vibration to the control interface.

The *ergonomics* coding classifies suggestions related to improving the physical control interface attributes, such as reducing the pushing difficulties for locking the container to the truck task, a smaller joystick, softer buttons, a lighter joystick, and design considerations for female user.

The *problem detection* coding groups the additional feedback to indicate dangers to the operator and vibration as a signal output for problem detection. Next, the *improve the traction* coding refers to suggestions to reduce joystick traction during the pushing and pulling tasks. Then, the *time delays* coding refers to the suggestion to improve the time lag between physical operation displayed on the display and the control interface. Finally, the *tough interface for repetitive usage* coding refers to the suggestion of using a softer and lighter material for the joystick interface but one that is durable enough for repetitive pushing and pulling activity.

4.1.4 UX goals

Based on the positive UX results presented in Figure 8, the existing ROS design already provides remote operators with an acceptable level of safety in relation to the safety risks, generally has good ergonomics, and the operators commonly experience low mental workload during their control and handling activities. Therefore, these three positive experience categories should be excluded from being the UX goals of this research. The other experiences—namely minimal manpower requirements, increased time performance, reduced operation task complexity, less frequent maintenance, and easy handling—will be compared to the negative experience results in order to search for similar findings.

The results presented in Figure 11 show the negative experiences are time delays; problems in detecting an error in the ROS system; the lack of communication options between the operators, the interface, and people in the working terminal; and visual limitations (such as limited monitor size and problems in handling smoothness due to force and traction). These five categories will be accounted for as the main UX goals, and they will be evaluated further in the conjoint analysis [7]. The results shown in Figure 15 support the user's negative experiences by sharing similar answer coding and definitions, such as *problem detection*, *communication options*, and *ergonomics*.

Table 4 summarizes the results from this study by tabulating the main UX goals that are derived from the obtained results of the investigation. These goals have been formulated with the objective of overcoming the lack of direct motion feeling through the joystick interface, particularly in remote container crane applications.

Table 4 The main UX goals of the remote joystick interface design

No.	UX Goals
1	Reduce time delays
2	Problem detection
3	Communication options
4	Reduce visual limitations
5	Handling smoothness
6	Ergonomics

4.1.5 UX Goal 1: Reduce time delays

Based on the task and time analysis, time delays occur during the following manual operations:

i) The task of lowering the spreader to load a container.
ii) The task of lifting the spreader to unload a container.

Based on the observations, the time delays during manual loading tasks are due to the fact that the spreader moves after a delay at the beginning of the operation and is still moving at the end of the task, even after the operator performs the *stop* operation. The time delays in unloading tasks are due to the same reason experienced in manual loading tasks, and the spreader already stops moving even when the operator is still performing a *lift up* operation.

Figure 16 shows the time delays experienced during the manual loading task. On average, the time delay for a manual loading task was 3.12 s. The longest delay time was 10.00 s while the shortest time delay was 1.00 s.

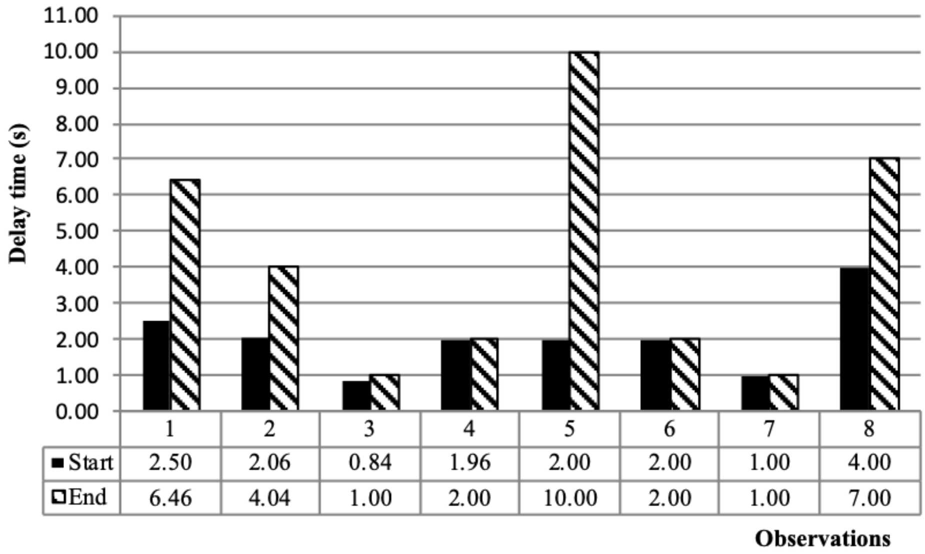
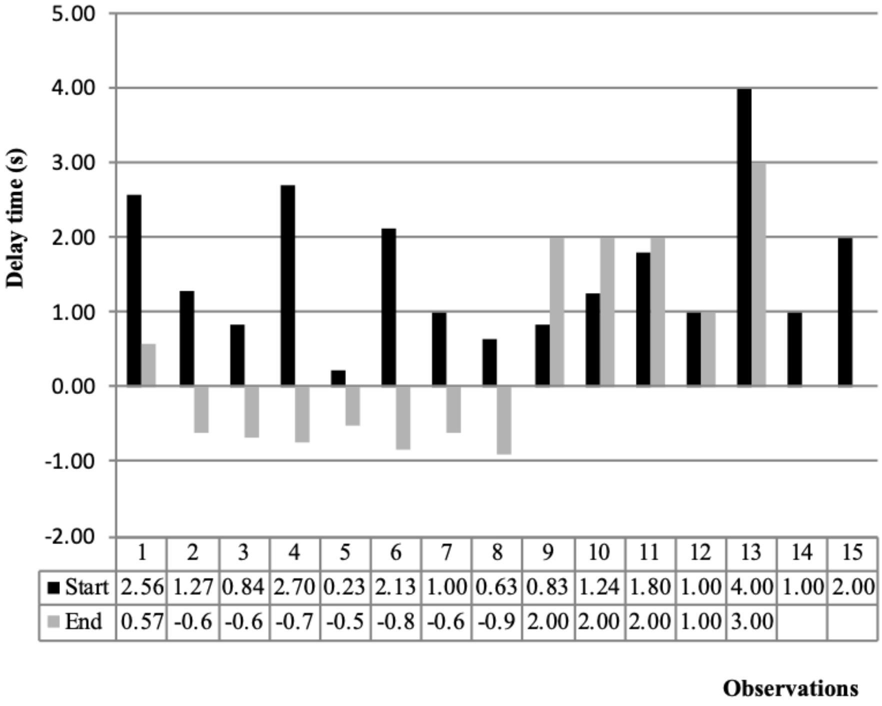


Figure 15 The results regarding time delays between joystick and spreader movement in a manual loading task

Figure 17 shows the time delays experienced during the manual unloading task. Positive values show that the spreader stops after a delay from when joystick operation stops, and the negative values show that the spreader stops before the task is finished. On average, the time delay for the manual unloading task was 1.38 s. The longest delay was 4.00 s while the shortest delay was 0.23 s.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
■ Start	2.56	1.27	0.84	2.70	0.23	2.13	1.00	0.63	0.83	1.24	1.80	1.00	4.00	1.00	2.00
■ End	0.57	-0.6	-0.6	-0.7	-0.5	-0.8	-0.6	-0.9	2.00	2.00	2.00	1.00	3.00		

Figure 16 The results regarding time delays between joystick and spreader movement in a manual unloading task

4.1.6 UX Goal 2: Problem detection

Figure 18 shows the results from the questionnaire interviews regarding the joystick as a control and handling interface. Eleven out of thirteen operators strongly agreed that using the current joysticks helped them in handling the crane operation, while one operator disagreed as she had found that the handling spreader was in a tilting position that was not detected and was hidden from camera views.

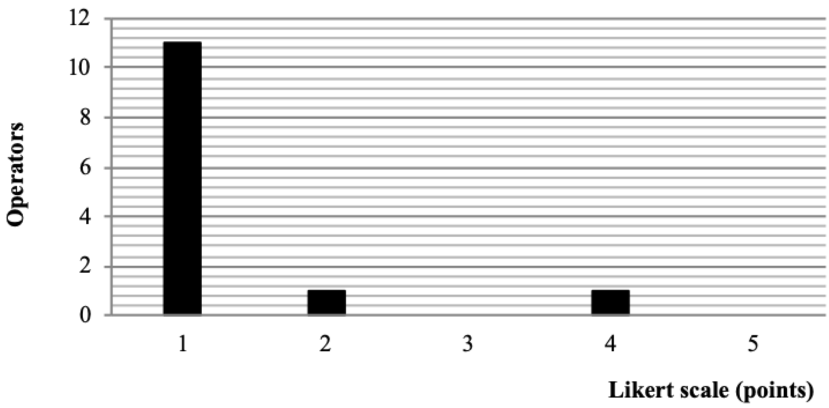


Figure 17 The questionnaire results regarding the joystick as a control and handling interface

From the interview results, it can be seen that all the operators agreed that adding a safety indicator to the joystick interface could help detect the blind-spot problem, such as that described where the spreader moved into a tilting position.

From the observations, the joystick already aided operators by providing multiple operational buttons for camera views, skew, a *stop* operation, an *open* and *close* twistlock, and spreader micro-move functions as shown in Figure 19, but there was no button for problem detection. The users are forced to rely only on the display monitor and closed-circuit TV to view the operation problems in the blocks.

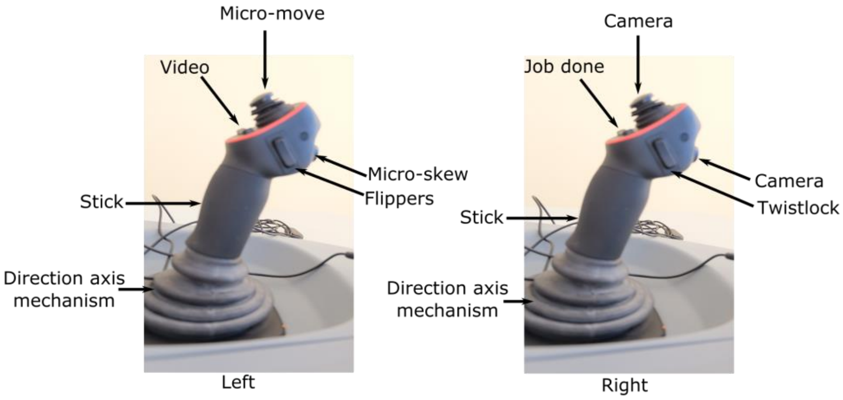


Figure 18 The operational buttons on the joystick interface for remotely controlling and handling cranes

Figure 20 illustrates the results for the mean time taken for each task involved in the remote control and handling of crane operation that are specific to loading and unloading a container. The most amount of time is taken when lowering the spreader, which takes 21.75 s, followed by moving the trolley forward, which takes 16.58 s.

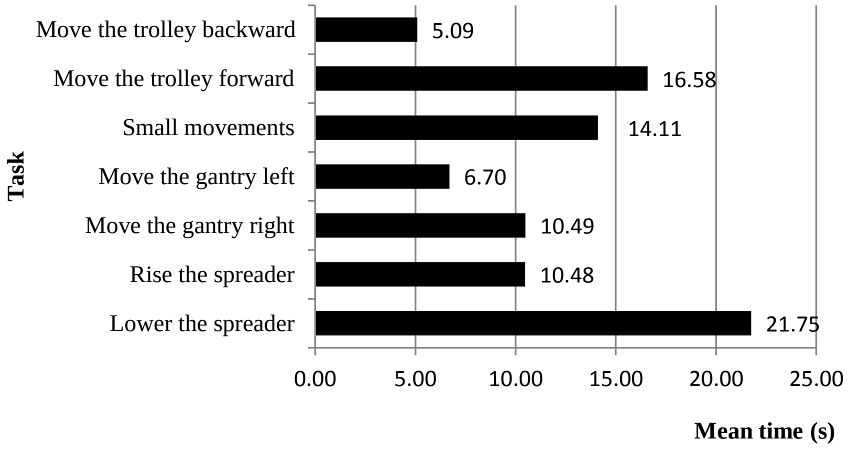


Figure 19 Results regarding the mean time for each task in the remote control and handling operation

Task analysis shows that the tasks of lowering and raising the spreader are conducted by operators while some other tasks are automated (e.g., moving trolley forward and backward, moving the gantry left and right). Besides these tasks, small movements—such as skewing, changing the camera, locking and unlocking the twistlock—could be either automated or manually operated based on the operation requirements. It was observed that the tasks were conducted without specific sequences and depended on the operation type (e.g., loading a container onto a truck or a container stacking operation). Usually, a stacking operation is performed by a fully automated system, but in certain conditions, the operators were required to stack the containers remotely, especially when an error occurred in the automatic system.

4.1.7 UX Goal 3: Communication options

The communication options in this study refer to the joystick interface's capability to help the operator to interact with the ROS system and people in terminal blocks both during and before an emergency situation.

Figure 21 presents the questionnaire results relating to the communication options during control and handling of the cranes remotely, based on Likert scale points. The results show that ten operators strongly disagreed that the existing joystick interface was able to identify a potential error, eight strongly disagreed that the joystick interface was able to identify a potential accident, and six strongly disagreed that the joystick interface was able to communicate with operators.

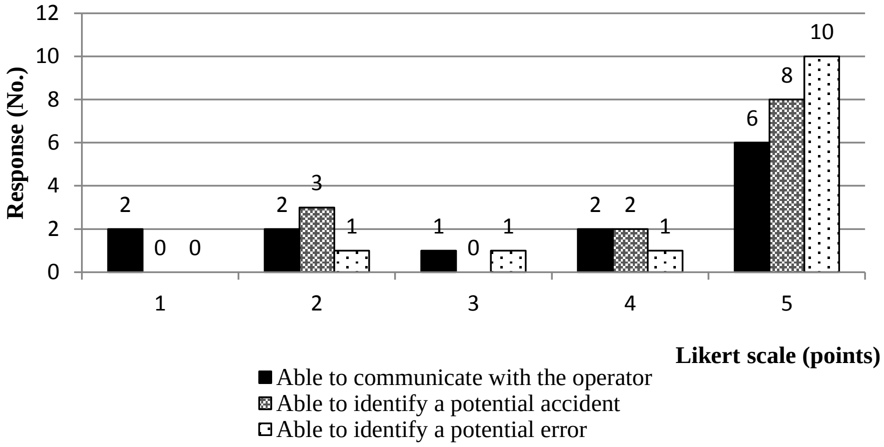


Figure 20 Results regarding the feedback on the communication options in the remote control and handling operation

From the interview results, we can see that twelve operators used the computer display and GUI as the main communication option, six operators viewed through the office windows, and five watched CCTV.

4.1.8 UX Goal 4: Reduce visual limitations

Figure 22 shows the results of the pushing time, which is related to the repetitive number of joystick pushes performed during the task of lowering the spreader. The longest time, reflected in the highest number of joystick-push repetitions, was 45.00 s (for twelve pushes).

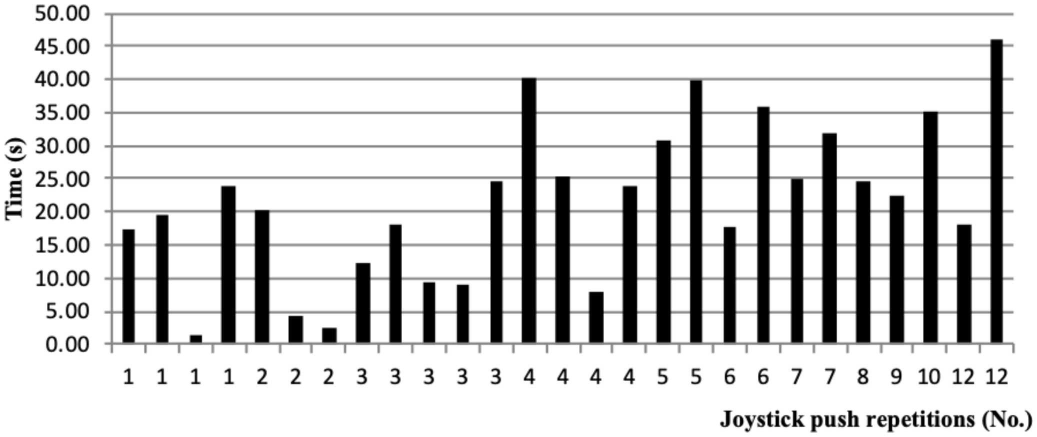


Figure 21 Results on the comparison between task time and joystick push repetitions during the task of moving down the spreader

From the observation results, the operators took a long time and pushed the joystick repetitively when the container was close to a truck or container stack. This is because the operator experienced difficulties in estimating the distance between the container's bottom and the truck, based on the monitor visual. In addition, the operators experienced blind spots while performing the loading operation (e.g., under the container), an unclear zoom view due to graphic quality or bad weather (e.g., heavy rain, morning glare during sunrise), and a lack of lighting during night-time operation.

4.1.9 UX Goal 5: Handling smoothness

The open-ended interview results show that four operators stated that the joystick weight and traction influenced the smoothness of the joystick movements. Figure 23 supports this response by showing the awkward position of the operator's hand and fingers during operation of the joystick. In the figure the operators hook their fingers around the table edge in order to maintain the joystick position.

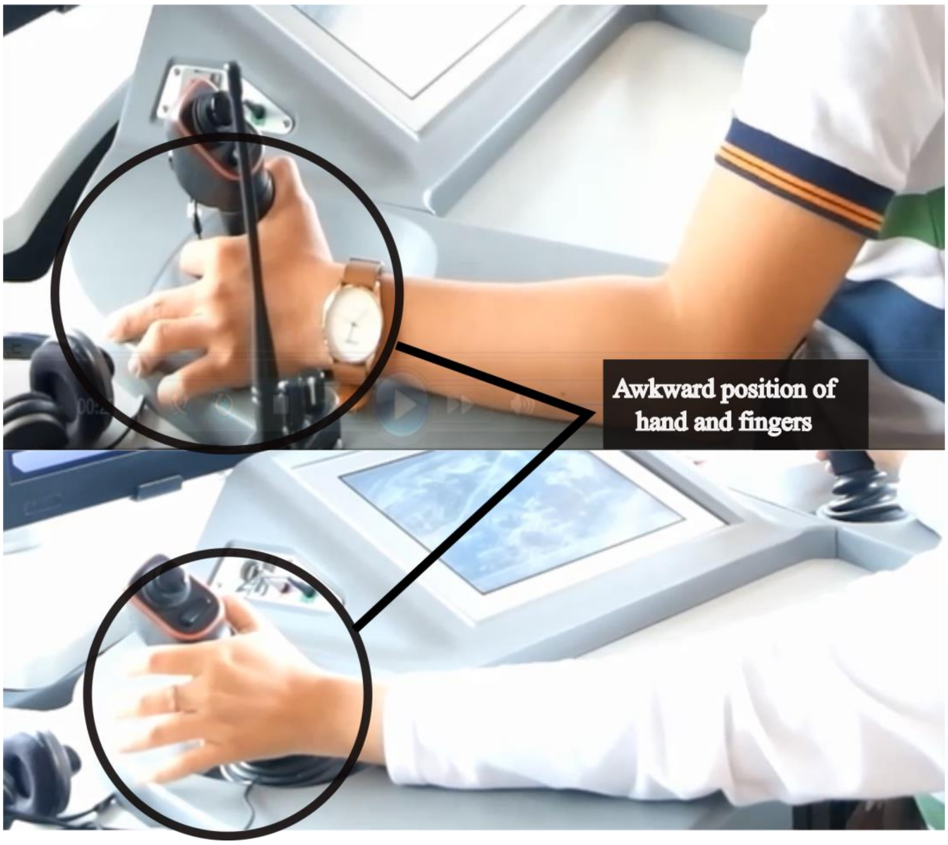


Figure 22 The awkward position of hand and fingers during operation of a joystick

4.1.10 UX Goal 6: Ergonomics

Figure 24 illustrates the open-ended interview results on possible accidents in the terminal blocks during remote operations based on the operators’ experiences. Twelve operators suggested that the main accident factor is poor focus during operation (e.g., feeling tired). Eleven operators suggested that they failed to see an object or people, for example, during heavy rain or when hidden from view, and ten operators suggested that they were ill. The other factors are unstable emotions, working long hours, stress, a lack of experience, disabilities, a lack of interest in doing the task, age, being too comfortable, etc.

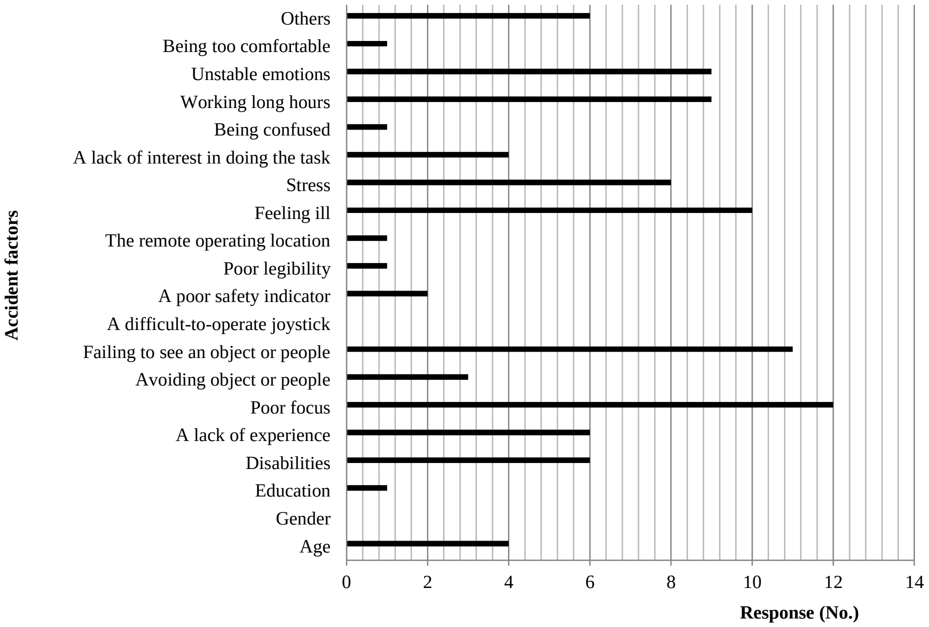


Figure 23 Results on the possible accident factors during remote operations

Figure 25 presents the data on musculoskeletal pain among operators based on the Nordic checklist results. Nine operators experienced neck pain, four had wrist or hand pain, three had lower back pain, two had shoulder pain, and one operator had elbow pain.

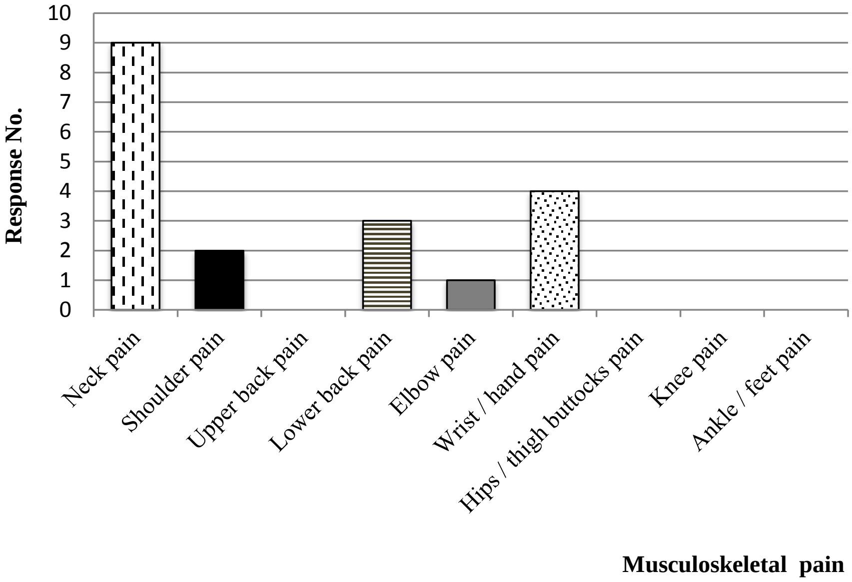


Figure 24 Results on the musculoskeletal pain checklist

Table 5 shows the summary results of the initial ergonomics risk assessment (ERA) according to the musculoskeletal pain claimed to be felt by the operators in Figure 25. The results show that all the operators are exposed to static and sustained work posture risk factors and repetition risk factors. A static and sustained work posture contributes to neck pain and lower back pain, while repetitive work contributes to elbow pain, wrist or hand pain, and shoulder pain, as shown in Table 5. An example of the static and sustained work posture risk situation is illustrated in Figure 26 and an example of repetitive work is discussed in section 3.3.9 and also illustrated in Figure 27.

Table 5 Summary results of the initial ergonomics risk assessment (ERA)

B		C		D		E		F		G							
Total score (13)		Total score (3)		Total score (1)		Total score (5)		Total score (4)		Total score (1)		Total score (1)		Total score (1)		Total score (2)	
Awkward postures	Need advanced ERA?	Static and sustained work posture	Need advanced ERA?	Repetition	Need advanced ERA?	Forceful exertion	Need advanced ERA?	Vibration	Need advanced ERA?	Lighting	Need advanced ERA?	Temperature	Need advanced ERA?	Ventilation	Need advanced ERA?	Noise	Need Advanced ERA?
Min. requirement for advance ERA (≥6)		Min. requirement for advance ERA (≥1)		Min. requirement for advance ERA (1)		Min. requirement for advance ERA (≥1)		Min. requirement for advance ERA (≥1)		Min. requirement for advance ERA (1)		Min. requirement for advance ERA (1)		Min. requirement for advance ERA (1)		Min. requirement for advance ERA (≥1)	
4		2	YES	3	YES	0		0		0		0		0		0	
4		2	YES	3	YES	0		0		0		0		0		0	
4		2	YES	3	YES	0		0		0		0		0		0	
4		2	YES	3	YES	0		0		0		0		0		0	
4		2	YES	3	YES	0		0		0		0		0		0	
4		2	YES	3	YES	0		0		0		0		0		0	
4		2	YES	3	YES	0		0		0		0		0		0	
4		2	YES	3	YES	0		0		0		0		0		0	
4		2	YES	3	YES	0		0		0		0		0		0	
4		2	YES	3	YES	0		0		0		0		0		0	
4		2	YES	3	YES	0		0		0		0		0		0	
4		2	YES	3	YES	0		0		0		0		0		0	
4		2	YES	3	YES	0		0		0		0		0		0	

B= Awkward posture, C= Static and sustained work posture, D= Repetitive motion,

E= Forceful Exertion, F= Vibration, G= Environmental factors

Figure 25 The static and sustained sitting posture during remote operation

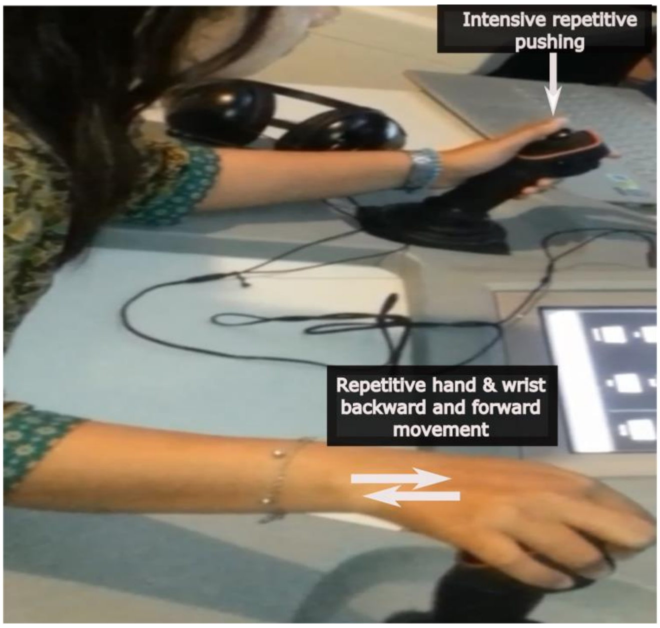


Figure 26 Repetitive work during remote operation

4.1.11 Conjoint analysis of UX goals

Table 6 presents the conjoint or relative importance analysis results regarding the UX goals this study. From the analysis, the *communication options* goal demands first priority with 25.00% of the operators' feedback, followed by *time delays* and *problem detection* in joint second ranking, each with 19.23% of the feedback, then comes the *ergonomics* goal with 17.31% of the feedback, and the lowest priority goals are *visual limitations* and *handling smoothness,* each with 9.62% of the feedback.

Table 6 The results of conjoint analysis of the UX goals

UX goals	**Frequency of answers**			**Percentage**	**Hierarchy**
	(Problems)	(Suggestions)	(Total)	(%)	
Reduce time delays	9	1	10	19.23	2
Problem detection	8	2	10	19.23	2
Communication options	6	7	13	25.00	1
Reduce visual limitations	5	0	5	9.62	4
Handling smoothness	4	1	5	9.62	4
Ergonomics	3	6	9	17.31	3
			52		

4.2 A list of design metrics for UX goal communication options and problem detection

4.2.1 Design specifications

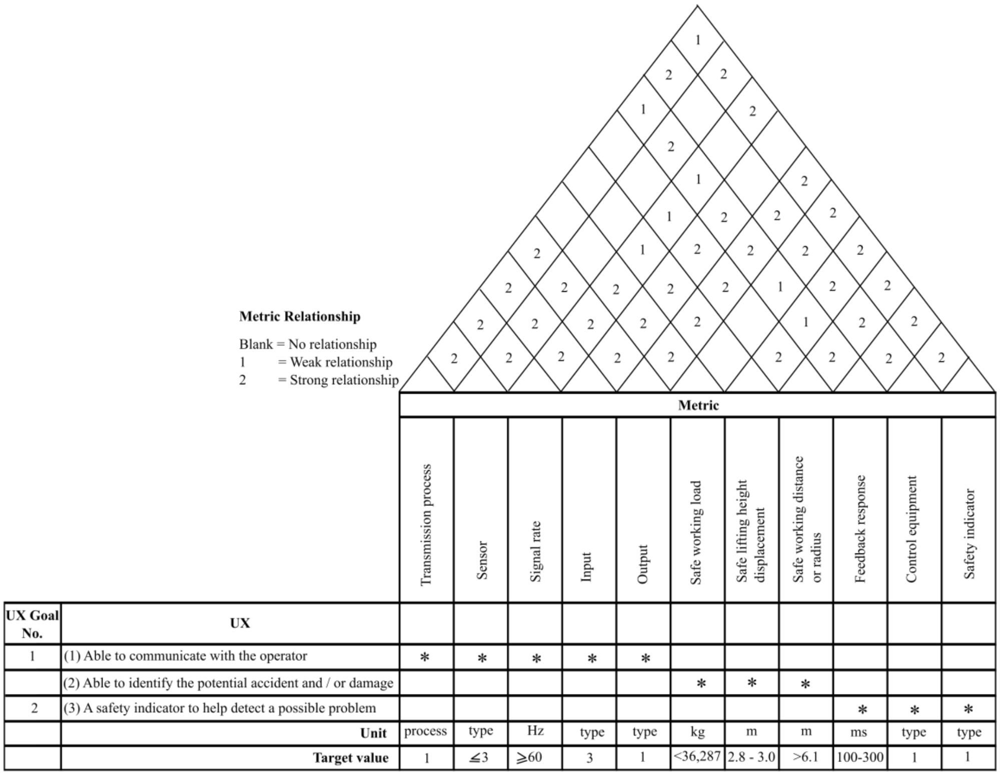
Table 7 shows the results of the design specifications for the *problem detection* and *communication options* goals. There are two translated UXs for the first UX goal, which is being able to communicate with the operator and identify a potential accident and damage. The metrics for the first translated UX are the transmission process, data rate, signal rate, and the input and output of communication, while the metrics for the second translated UX are a safe working load, safe lifting height displacement, and a safe working distance or radius. The translated UX for the second UX goal is a safety indicator to detect possible problems with the metrics of feedback response, control equipment, and a safety indicator. Each metric is measured by an SI unit and its target value in order to achieve the UX and UX goals (as shown in Table 7).

Table 7 Design specification for the joystick interface for the remote-operated station (ROS) for crane operation

UX goal	UX	Metric	Unit	Target value
(1) Communication options	(1) Being able to communicate with the operator	Transmission process [124]	process [125]	1 [125]
		Sensor [76]	type [126]	≤ 3[126]
		Signal rate [76]	Hz [76]	≥ 60 [127]
		Input [124]	type [76]	3
		Output[124]	type [76]	1
	(2) Being able to identify a potential accident and/or damage	Safe working load [76]	kg [128]	<36.287 [129]
		Safe lifting height displacement [76]	m [128]	2.8–3.0 [129]
		Safe working distance or radius [76]	m [128]	>6.1 [130]
(2) Problem detection	(3) Safety indicator to help detect a possible problem	Feedback response [76]	ms [76]	100–300 [131][132]
		Control equipment [76]	type [128]	1
		Safety indicator [76]	type [76]	1

4.2.2 QFD

Figure 28 illustrates the QFD diagram for the *communication options* and *problem detection* goals. Based on the results presented in Sections 4.1.6, 4.1.7, and 4.2.1, the UX goal of *communication options* contributes to a domino or mechanical effect on the UX goal of *problem detection*. The domino effects between the metrics of both goals are presented by the scale points of the metrics' relationship in the diagram. As an example, the metric of the transmission process for being able to communicate with the operator experience is strongly affected by the data rate, signal rate, input, output, and control equipment, while it is less affected by a safety indicator and not affected by a safe working load, safe working height displacement, or a safe working distance or radius.



UX Goal No.	UX	Transmission process	Sensor	Signal rate	Input	Output	Safe working load	Safe lifting height displacement	Safe working distance or radius	Feedback response	Control equipment	Safety indicator
1	(1) Able to communicate with the operator	*	*	*	*	*						
	(2) Able to identify the potential accident and / or damage						*	*	*			
2	(3) A safety indicator to help detect a possible problem									*	*	*
	Unit	process	type	Hz	type	type	kg	m	m	ms	type	type
	Target value	1	≤3	≥60	3	1	<36,287	2.8 - 3.0	>6.1	100-300	1	1

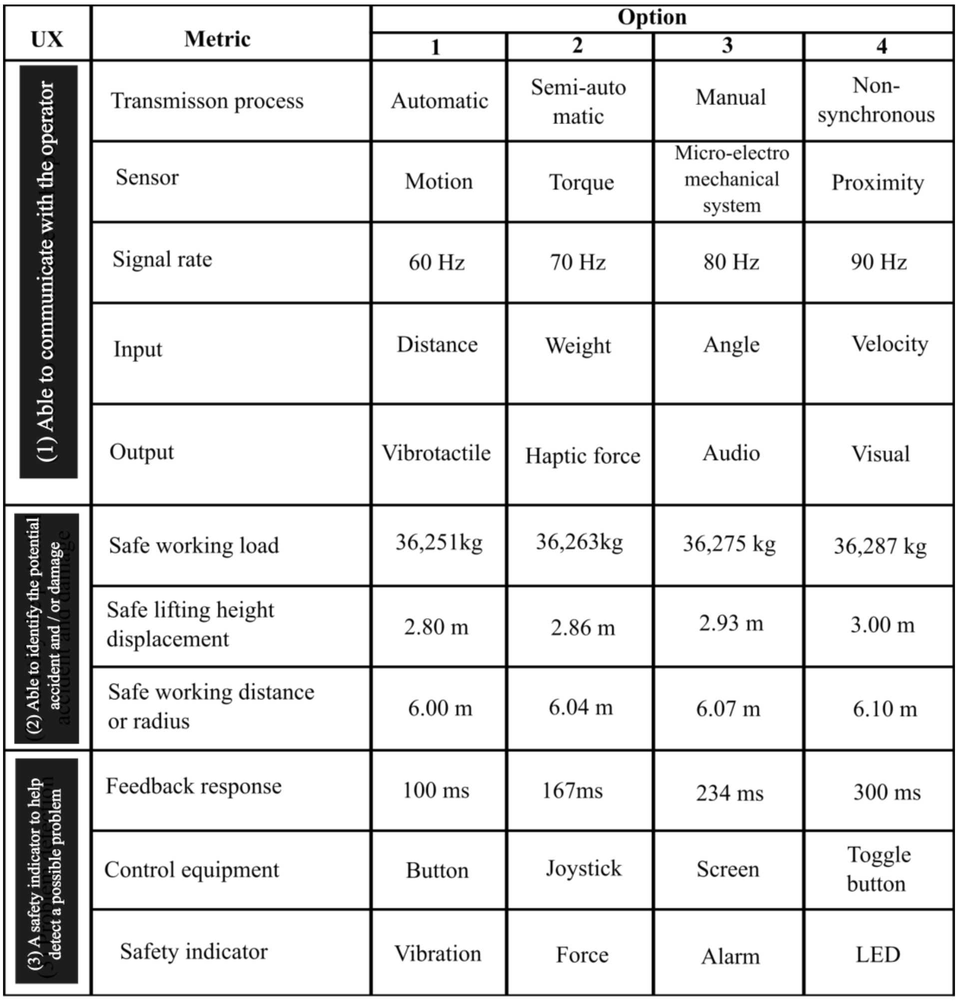
Figure 27 Analysis results for communication *options* and *problem detection* goals, shown on a QFD diagram

4.2.3 Morphology chart

Table 8 presents the analysis results in the form of a morphology chart. Five solution options are suggested in the morphology chart for each UX metric [66, 76]. The solution options for the transmission process are *automatic*, *semi-automatic*, *manual* [125], and *non-synchronous* [133]. The solution options for the sensor are *motion*, *torque*, *a micro-electro mechanical system* (MMS), and *proximity* [134], while the solution options for the signal rate are 60 to 90 Hz [135]. *Distance*, *weight*, *angle*, and *velocity* [136] are the solution options for input, and finally *vibrotactile* [137], *haptic force* [92], and *audio and visual* [127] are the output solution options. The metric solution options for the second UX are 36,251 to 36,287 kg for the safe working load [129], 2.80 to 3.00 m for the safe lifting height displacement [129], and 6.00 to 6.10 m for the safe working distance or radius [129]. Finally, the solution options for the third

UX metric are 100 to 300 ms for the feedback response [132], button [138], joystick [92], screen [139], and toggle button [138] as the control equipment, and finally vibration [140], a force [92], an alarm [141], and an LED [142] as safety indicators.

Table 8 The results of the morphology chart analysis

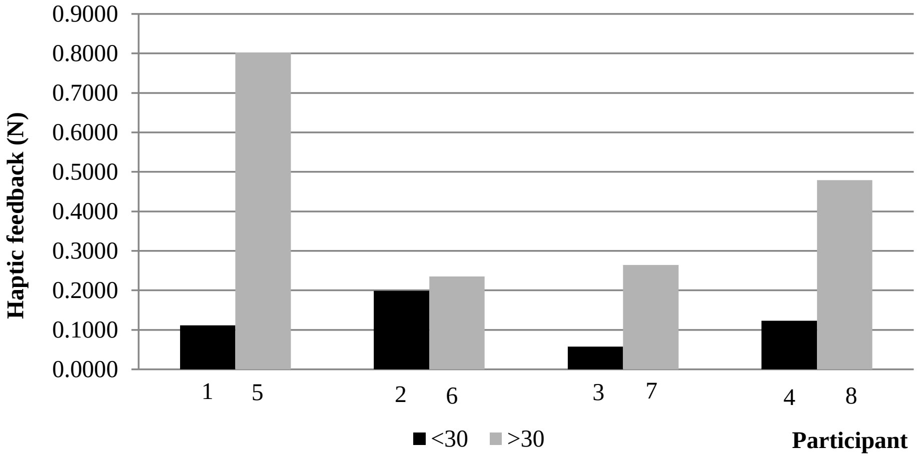


UX	Metric	Option			
		1	2	3	4
(1) Able to communicate with the operator	Transmisson process	Automatic	Semi-auto matic	Manual	Non-synchronous
	Sensor	Motion	Torque	Micro-electro mechanical system	Proximity
	Signal rate	60 Hz	70 Hz	80 Hz	90 Hz
	Input	Distance	Weight	Angle	Velocity
	Output	Vibrotactile	Haptic force	Audio	Visual
(2) Able to identify the potential accident and / or damage	Safe working load	36,251kg	36,263kg	36,275 kg	36,287 kg
	Safe lifting height displacement	2.80 m	2.86 m	2.93 m	3.00 m
	Safe working distance or radius	6.00 m	6.04 m	6.07 m	6.10 m
(3) A safety indicator to help detect a possible problem	Feedback response	100 ms	167ms	234 ms	300 ms
	Control equipment	Button	Joystick	Screen	Toggle button
	Safety indicator	Vibration	Force	Alarm	LED

4.3 Results of haptic feedback effects in ORV remote control operation

Figure 29 shows the results of the haptic feedback that triggers the user’s hand movement in relation to the age factor. The highest response force among the age group of those below 30 years of age was 0.1991 N, compared to 0.8028 N for those in the age group of those above 30. The lowest response force was 0.0575 N and 0.2352 N for those under 30 and those above 30, respectively. The average response force was 0.1225

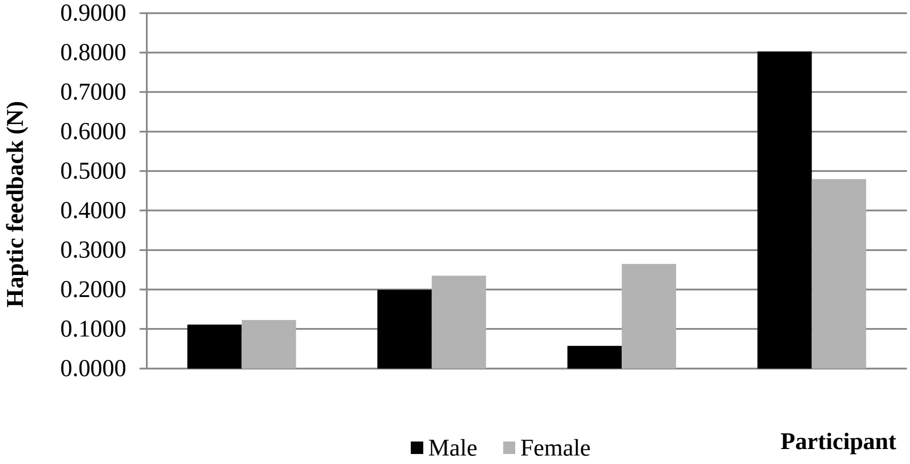
N among those participants below 30 compared to 0.4455 N for those above 30. The *P* value from the *t*-test result is 0.0476, which provides enough evidence to reject the null hypothesis. Therefore, there is significant mean difference in the haptic feedback between those participants below 30 years of age and those above 30 years of age, with a confidence interval of 0.05.



Mean $_{<30}$ = 0.1225N Mean $_{>30}$ = 0.4455N P= 0.0476 α = 0.05

Figure 28 Results of the haptic feedback in relation to the age factor

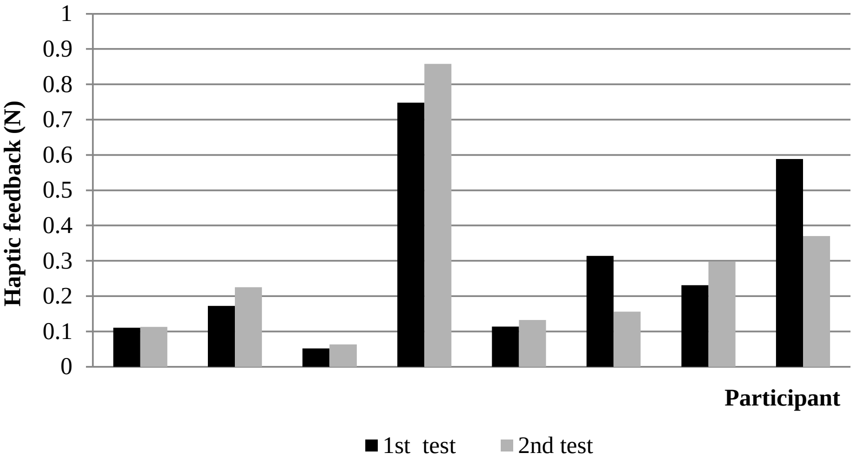
Figure 30 shows the results of the haptic feedback force that triggers the user's hand movement in relation to the gender factor. The highest response force required among males in order to get their reaction during haptic joystick usage was 0.8028 N, compared to 0.4794 N among females. The lowest response force was 0.0573 N and 0.1228 N for the male group and female group respectively. The average response force was 0.2926 N among male participants, compared to 0.2755 N for female participants. The *P* value from the *t*-Test result is 0.4659, which fails to reject the null hypothesis. Therefore, there is not enough statistical evidence to show a significant mean difference in haptic feedback between male participants and female participants, with a confidence interval of 0.05.



Mean $_{\text{male}}$ = 0.2926N Mean $_{\text{female}}$ = 0.2755N P= 0.4659 α = 0.05

Figure 29 Results regarding haptic feedback in relation to the gender factor

Figure 31 shows the results regarding the haptic feedback response force in relation to the rest effect factor. The highest response force in the first test was 0.7478 N, compared to 0.8577 N in the second test. The lowest response force was 0.0515 N and 0.0630 N for first test and second test respectively. The average response force was 0.2912 N in first test, compared to 0.2770 N in the second test. The *P* value from the *t*-test result was 0.4560, which fails to reject the null hypothesis. Therefore, there is not enough statistical evidence to show a significant mean difference in haptic feedback between before and after rest, with a confidence interval of 0.05.

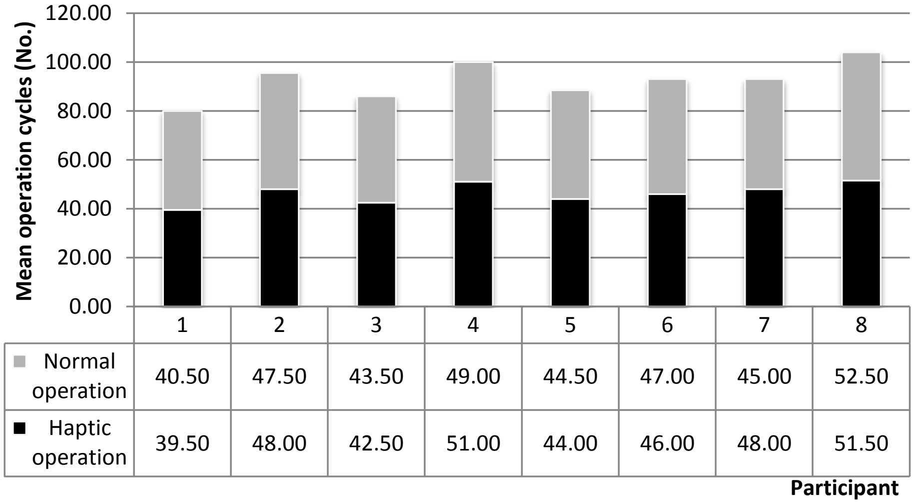


Mean $_{\text{test1}}$ = 0.2912N Mean $_{\text{test 2}}$ = 0.2770N P= 0.4560 $\alpha = 0.05$

Figure 30 Results regarding the haptic feedback in relation to the rest effect factor

4.4 Results of usability testing of haptic feedback interface of remote-operated ORV

Figure 32 presents the results for the number of completed operation cycles in ten minutes of testing. The results represent the effectiveness of the haptic feedback and joystick compared to the normal joystick that is used for the remote control and handling operation. It is shown that the average number of cycles completed by eight operators when using the haptic joystick was 46.31, and when using the normal joystick it was 46.19 cycles. The maximum number of operation cycles when using the haptic joystick was 51.50 and when using the normal joystick it was 52.50 cycles. The minimum number of operation cycles when using the haptic joystick was 39.50, compared to 40.50 cycles when using the normal joystick. The *P* value from the *t*-test was 0.47. Therefore, there is insufficient statistical evidence to reject the null hypothesis, with a 0.05 significance level.

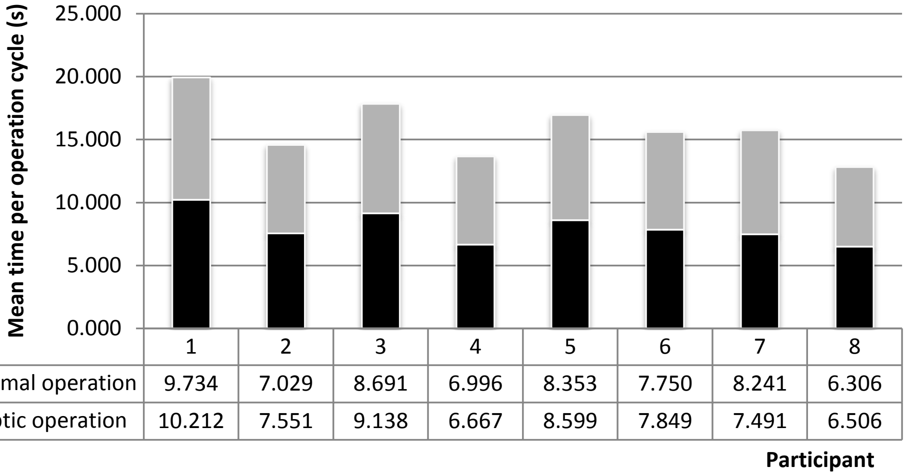


	1	2	3	4	5	6	7	8
▨ Normal operation	40.50	47.50	43.50	49.00	44.50	47.00	45.00	52.50
■ Haptic operation	39.50	48.00	42.50	51.00	44.00	46.00	48.00	51.50

Mean C_{haptic} = 46.31 Mean C_{normal}= 46.19 P= 0.47 α = 0.05

Figure 31 Results for the number of completed operation cycles in ten minutes of testing

Figure 33 shows the results for task time when using the haptic joystick and normal joystick. These results represent the efficiency of using haptic feedback and a haptic joystick compared to a normal joystick. The mean time for a task is 8.001 s when using the haptic joystick and 7.888 s when using the normal joystick. The maximum time per task when using the haptic joystick was 10.212 s, compared to 9.734 s when using the normal joystick. The minimum time per task is 6.506 s when using the haptic joystick, compared to 6.306 s when using the normal joystick. The *P* value from the *t*-test was 0.42. Therefore, there is not enough statistical evidence to reject the null hypothesis, with a 0.05 significance level.



	1	2	3	4	5	6	7	8
■ Normal operation	9.734	7.029	8.691	6.996	8.353	7.750	8.241	6.306
■ Haptic operation	10.212	7.551	9.138	6.667	8.599	7.849	7.491	6.506

mean t_{haptic} = 8.001s mean t_{normal}= 7.888s P= 0.42 $\alpha = 0.05$

Figure 32 Results regarding task time

Figure 34 shows the summary results of the frequency of answers using Likert-scale points relating to the haptic joystick usage satisfaction in regard to safety purposes. Four operators responded with the second point on the scale (*very good*) for overall satisfaction when using the haptic joystick during testing, two operators responded with the third point on the scale, and two gave the first point. The highest response relates to stress level satisfaction, for which six operators gave the first point on the scale (*excellent satisfaction*). Five operators responded by giving the second point for both confidence satisfaction and interface quality satisfaction. Also, five operators answered by giving the first point on the scale for feeling satisfaction.

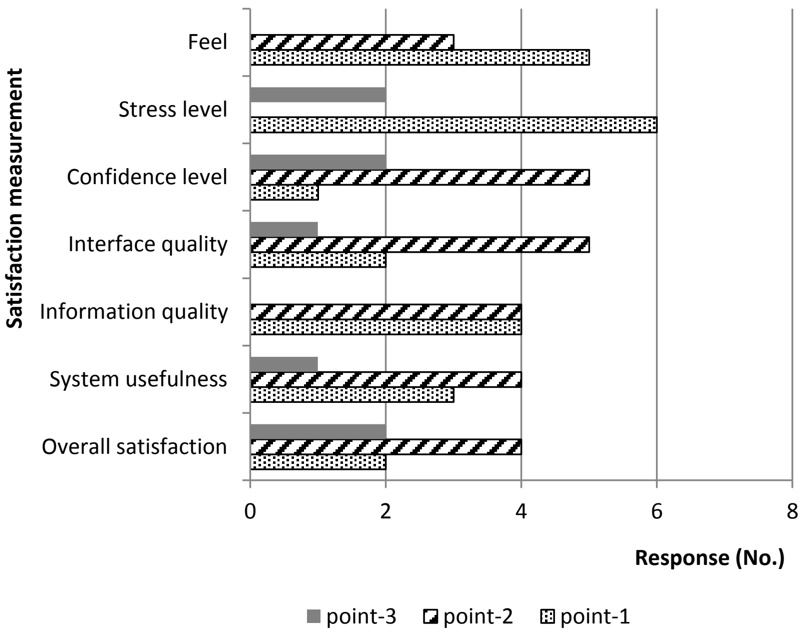


Figure 33 Summary results for satisfaction regarding haptic joystick usage for safety purposes

5 Findings

Firstly, no UX studies regarding the lack of direct motion feeling of a ROS for a container crane application can be found in the literature. Existing research related to remote-operated cranes are often related to software development [143], hardware development [16, 21, 143], and UXs of physical operation [10, 17]. The UX goals—such as reduced time delays, problem detection, communication options, reduce visual limitations, handling smoothness, and ergonomics—were not proposed in the reference articles.

Secondly, the establishment of design specifications, QFD, and a morphology chart with which to translate UX goals into a set of possible, precise, and measurable technical criteria was considered novel. The methods and tools are already established in the engineering design process, but the implications regarding them found in this study open up new possibilities and ideas with which to map the human factors to the technical parameters in ORV design and development.

Thirdly, the results from the haptic feedback and usability study produced important findings for haptic control and handling interface design for the remote-operated ORV application. It was found that the response force from the participants while using the haptic joystick did not yield significantly different results between genders or when considering a rest factor, but there was a significant difference in force between age groups which is, the average haptic results show that older users, i.e., those above 30 years of age, respond more to higher haptic force as a warning signal compared to younger users, i.e., those under 30. It was also found that using haptic feedback for simple operations does not have a significant influence on increasing the user’s effectiveness and efficiency. The reason behind these results is that the force applied on the operator’s palm slows down hand-pushing movements as a reaction to ensuring that the spreader avoids colliding with the container during operation, due to the high approach speed. Also, from the interviews it was found that the operators claimed that haptic feedback slowed down their hand movements because they needed to refocus on the task. The simple task given to the operators also possibly contributed to having insufficient evidence to prove that haptic joystick usage increased the users’ performance. The characteristics of some of the operators (i.e., age factor, health factor, adapting to haptics, and problems concentrating) also resulted in a small effectiveness and efficiency difference between haptic joystick usage and normal joystick usage. This small difference means that haptic joystick usage could possibly be more usable and increase user performance if it were applied in a complex remote control and handling operation, and if the multi-selection of haptic feedback for multiple groups of operators’ age and health factors were improved so as to improve control and handling satisfaction, and to minimize the surprise and confusion of operators. However, the satisfaction results on both haptic feedback information and the interface give positive feedback regarding the human elements, such as their perception of the system’s usefulness, the confidence aspect, stress, and feeling.

6 Conclusions

The main objective of this thesis was to establish novel methods for assessing and improving usability of a remote-operated ORV interface. The first aim was to develop a novel method to investigate the UX in human-machine interaction in order to obtain the UX goals in an ORV remote-operated control interface. The second aim was to establish a method for developing a list of design metrics based on UX goals. The third aim was to develop a novel method for assessing the effects of haptic feedback as one of the solutions for UX goals and the list of design metrics by using virtual environments and real-time simulator. The fourth aim was to develop a method to test the usability of a haptic feedback control interface of ORV using the virtual environments and a real-time simulator.

Two methods were developed based on the UCD approach, such as an investigation into the UX goals method, and analysis and evaluation methods for UX goals. The methods for the list of design metrics development were established based on an engineering design approach. Finally, four methods were established based on a user testing approach, i.e., haptic feedback testing, statistical analysis on haptic feedback hypotheses, usability testing and analysis, and evaluation on haptic usability.

At first, six UX goals for remote-operated crane design were produced based on eight positive experiences, eight negative experiences, and improvement suggestions. Next, a list of design metrics was established based on the two highest-ranking UX goals. Haptic feedback was suggested in the list of design metrics as one solution for UX goals. Therefore, haptic feedback was investigated in an ORV remote-operated control interface and the results showed a significant difference in haptic feedback between two age groups. The average haptic feedback was 0.1225 N among participants below 30 years of age and 0.4455 N for those above 30. In addition, the usability testing results showed that the mean value for haptic joystick effectiveness was 46.31 cycles and for a normal joystick it was 46.19 cycles in 10 minutes of operation. The mean efficiency when using a haptic joystick was 8.001 s, compared to 7.888 s when using a normal joystick. Finally, on average, user feedback for satisfaction was rated to be at the second point of the assessment scale (the haptic joystick was considered very good in regard to satisfaction) for the haptic joystick.

This thesis emphasizes direct-experience user exploration and investigation methods in establishing the design and development methods for a remote-operated ORV, which produced a set of UX goals, human factors, and their related design metrics, statistical data on haptic feedback, and usability data on haptic feedback and the haptic interface.

In the future, it is suggested that further studies to explore other UX goals should be conducted in order to investigate the relationship between human factors and design metrics in ORV design. Also, an investigation into the haptic feedback range for multiple groups of operators in regard to age and health is strongly suggested, in order to search for haptic feedback effectiveness and efficiency improvements for the target groups. Finally, a complex operational setup for usability testing is suggested for a future study, in order to validate the importance of haptic feedback usage in complex tasks in the remote control and handling of an ORV.

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Appendix A: The Demographic and UX Questionnaires

Dear participants,

This questionnaire is designed for operators that handle remote-operation cranes. The objectives for this questionnaire are:

(Perserta yang dihormati, Kuesioner ini dirancang untuk pengemudi yang menangani operasi derek jarak jauh. Tujuan untuk kuesioner ini adalah☺

1. To investigate the crane's operators' experiences of using a joystick to handle the remote-operation crane and containers.

   (Untuk menyelidiki pengalaman pengemudi-pengemudi derek menggunakan joystick untuk menangani derek dan kontena dari jarak jauh.)
2. To investigate the effects of remote-operation joystick handling on the crane's operators.

   (Untuk menyelidiki efek pengendalian joystick jarak jauh terhadap pengemudi derek.)

YOUR answers are very important to investigate the improvement of existing crane joystick design. Only YOU can provide the correct answers to our investigations. Please answers this questionnaire correctly and honestly. Any personal information will be recorded as secret data. This questionnaire will take a maximum of 30 minutes to complete.

(Jawaban ANDA sangat penting untuk menyelidik penambahbaikan desain joystick derek yang sudah ada . Hanya ANDA yan ompsa memberi jawaban yang benar untuk penyelidikan kami. Sebarang informasi pribadi akan disimpan sebagai data yang rahasia. Kuesioner ini akan mengambil maksimal 30 menit untuk diselesaikan.)

Thank you for taking the time to answer this questionnaire.

(Terima kasih untuk meluangkan waktu bagi menjawab kuesioner ini.)

Ummi Noor Nazahiah Abdullah

Researcher /*Penyelidik*

Personal information / *Informasi pribadi*:

1. Gender *(Jantina)* : Male *(Pria)* / Female *(wanita)* ***Circle the correct answer* / lingkarkan jawapan
2. Age *(umur)*: …………………..
3. Crane driving experience *(Pengalaman mengemudi derek):* …… years *(tahun)* ………… months *(bulan)*
4. Ethnicity *(Ras)* : ………………….

Section A: Operator experiences of using the current crane joystick to handle the crane and containers by remote operation.

(Bagian A: Pengalaman pengemudi menggunakan joystick derek pada saat ini untuk menangani derek dan kontena dari jarak jauh.)

1. Where did you operate the crane joystick *(Di mana anda mengemudi joystick derek)*?

   ……………………………………………………………………………………

2. How did you visualize the crane operation? Please select one of the following options. *(Bagaimana anda melihat derek beroperasi ?) Sila lingkarkan satu jawaban*
   a. Physically */ Secara fizikal*
   b. Using screens (e.g., a monitor, computer screen) / *Menggunaka ompuar contoh: monitor omputerer*
   c. Using electronic gadgets (e.g., iPad, mobile phone) / *Menggunakan gadget elektronik contoh: iPad, telepon bimbit*
   d. Some other way */ lain-lain*:

      ……………………………………………………...........

3. Please mark with an (X) / *Sila tandakan (X)*.

	Strongly agree *(Sangat setuju)*	***Agree*** *(Setuju)*	***Not sure*** *(Tidak yakin)*	***Disagree*** *(Tidak setuju)*	***Strongly disagree*** *(Sangat tidak setuju)*
a) It is difficult to control a crane using the current joystick (i.e., left, right, upward and backward movements). *(Sulit untuk mengontrol derek menggunakan joystick sedia ada seperti pergerakan kiri, kanan, ke atas dan ke bawah).*					
b) The current joystick did not function synchronously with the crane's boom and winch movement (i.e., its up and down speed, rotation speed). *(Joystick saat ini tidak berfungsi bersamaan dengan gerakan boom dan kerekan seperti kecepatan naik dan turun, kecepatan putaran).*					
c) The current joystick helps the operator be alert to the crane operation environment without looking at screens. *(Joystick saat ini membantu pengemudi waspada dengan lingkungan operasi derek tanpa melihat layar).*					
d) The current joystick assists the operator in handling crane operation excellently. *(Joystick saat ini membantu operator mengendali derek dengan sangat baik).*					
e) The current crane joystick is bulky. *(Joystick derek saat ini bersaiz besar).*					
f) The current crane joystick is stiff *(Joystick derek saat ini keras).*					

	Strongly agree *(Sangat setuju)*	***Agree*** *(Setuju)*	***Not sure*** *(Tidak yakin)*	***Disagree*** *(Tidak setuju)*	***Strongly disagree*** *(Sangat tidak setuju)*
g) The current crane joystick irritates the skin on my palm after long periods of operation. *(Joystick derek saat ini mengiritasi kulit telapak tangan untuk operasi waktu jangka panjang).*					
h) There are too many buttons on the current crane joystick. *(Ada terlalu banyak tombol pada joystick derek saat ini).*					
i) The current crane joystick requires frequent service and repair. *(Joystick derek saat ini sering membutuhkan perbaikan).*					
j) The current crane joystick is the latest technology product. *(Joystick derek saat ini adalah produk teknologi terbaru).*					
k) I easily adapt to the current crane joystick's handling operation. *(Saya mudah beradaptasi dengan pengendalian operasi joystick derek saat ini).*					
l) I experienced or almost experienced an accident during operation of the crane. *(Saya pernah atau hampir mengalami kecelakaan semasa mengendali derek).*					
m) I experienced or almost experienced container damage during operation of the crane. *(Saya pernah mengalami atau hampir mengalami kerusakan kontena semasa mengendali derek).*					

	Strongly agree *(Sangat setuju)*	***Agree*** *(Setuju)*	***Not sure*** *(Tidak yakin)*	***Disagree*** *(Tidak setuju)*	***Strongly disagree*** *(Sangat tidak setuju)*
n) The current crane joystick gives me direct safety indication feedback in order to avoid accidents and damage. *(Joystick derek saat ini memberi saya indikasi langsung kepada pengemudi untuk menghindari kecelakaan dan kerusakan).*					

o) What are the advantages of using the current joystick?

(Apakah keuntungan menggunakan joystick saat ini ?)

………………………………………………………………………………………

………………………………………………………………………………………

………………………………………………………………………………………

……………………………………………………………………………………....

p) What are the limitations/weaknesses of using the current joystick?

(Apakah keterbatasan / kelemahan menggunakan joystick saat ini?)

………………………………………………………………………………………

………………………………………………………………………………………

………………………………………………………………………………………

………………………………………………………………………………………

q) Please suggest any improvements that could be made regarding the current crane joystick.

(Sila sarankan apa-apa perbaikan yang harus dilakukan berkenaan joystick derek saat ini.)

………………………………………………………………………………………

………………………………………………………………………………………

Section B: The effects of crane joystick handling on the crane's driver.

(Bagian B: Pengaruh pengemudian joystick derek terhadap pengemudi derek.)

1. From your experiences, what are the factors that contribute to accidents while handling the crane remotely? (Insert an X for all that apply).

   (Dari pengalaman anda,apakah faktor-faktor yang berkontribusi kepada kecelakaan semasa mengemudi derek dari jarak jauh? (Anda bisa 'X' lebih dari satu jawaban)

   ○ Age/*Umur*
   ○ Gender/*Jantina*
   ○ Education/*Pendidikan*
   ○ Disability/*Cacat*
   ○ A lack of experience */ Kurangnya pengalaman*
   ○ Operator focus is interrupted */ Fokus terganggu*
   ○ Avoiding an unexpected object or person / *Menghindari objek atau orang yang tak terduga*
   ○ Failing to see an object or person / *Gagal melihat suatu objek atau orang*
   ○ Difficulties in operating the joystick / *Sulit untuk mengemudi joystick*
   ○ A poor safety indicator on the control station */ Indikator keselamatan yang kurang lengkap di stasion kawalan*
   ○ Poor legibility / *Tanda arahan kurang lengkap*
   ○ The remote operating location / *Lokasi kawalan yang jauh*
   ○ Feeling ill / *Sakit*
   ○ Stress / *Tekanan*
   ○ A lack of interest in doing the task / *Kurangnya minat dalam melakukan tugas*
   ○ Being confused / *Bingung*
   ○ Working long hours/ *Bekerja dalam waktu yang lama*
   ○ Unstable emotions / *Emosi tidak stabil*

○ A lack of direct motion feeling (e.g., that which would result from a vibrating crane) / *Kurangnya deria rasa secara terus seperti kabin derek bergetar*
○ Being too comfortable / *Terlalu nyaman*
○ Other factors (please specify): / *Lain-lain, sila nyatakan:*……………………………......

2. How do you operate the joystick?
   (Bagaimana anda mengemudikan joystick?)
   ○ With my right hand / *Dengan tangan kanan*
   ○ With my left hand / *Dengan tangan kiri*
   ○ With both hands / *Dengan kedua belah tangan*

3. What is your position when operating the joystick?
   (Bagaimana posisi nd aselama mengemudi joystick?)
   ○ Standing */ Berdiri*
   ○ Sitting */ Duduk*

4. Do you experience any uncomfortable situations when using the current joystick? (You can insert an X for more than one answer if your answer is “Yes”).
   (Apakah anda mengalami situasi yang tidak nyaman semasa menggunakan joystick sekarang? Anda bisa ’X’ lebih satu situasi jika jawaban anda ’Ya’
   ○ No/*Tidak*
   ○ Yes/*Ya*
      ○ Shoulder pain / Sakit bahu
      ○ Wrist pain / *Sakit pergelangan tangan*
      ○ Itchy skin on palm / *Gatal kulit telapak tangan*
      ○ Finger calluses due to repeated pushing and pulling activity / *Jari kapalan kerana aktivitas mendorong dan menarik berulang-ulang*
      ○ Eye strain / *Mata meregang*

○ Lumbago due to improper joystick distance / *Sakit pinggang kerana jarak joystick yang tidak tepat*

○ Other discomfort (please specify) / *Lain-lain, sila nyatakan*:

……………………………………………………..

5. How long can you grip the joystick for constantly during remote operation?

(Berapa lama anda bisa memegang joystick terus menerus semasa operasi kawalan jauh?

○ More than one hour / *Lebih dari satu jam*
○ Less than one hour / *Kurang dari satu jam*
○ Less than 30 minutes / *Kurang dari 30 menit*
○ Less than 10 minutes / *Kurang dari 10 menit*
○ Another period of time (please specify): / *Lain-lain, sila nyatakan*:

……………………………………………………………………………...

6. You found it is easy to control the joystick …

(Anda merasa bahwa mudah untuk mengontrol joystick...)

○ … for the first time / untuk pertama kali
○ … after several training sessions / selepas beberapa kali latihan
○ … after several years of work / selepas beberapa tahun bekerja
○ … (after another time period; please specify): / *Lain-lain, sila nyatakan*:

……………………………………………………………………………...

7. What do you feel during operation of the current crane joystick?

(Apa yang anda selalu alami selama mengemudi joystick derek saat ini?)

○ Happy/*Gembira*
○ Afraid/*Takut*

○ Angry/*Marah*
○ Sad/*Sedih*
○ Disgusted/*Jijik*
○ Trustful/*Percaya*
○ Anticipation/*Berharap*
○ Surprise/*Terkejut*
○ Another feeling (please specify): / *Lain-lain, sila nyatakan* :
…………………………………………………………………………...

8. Do you agree that working with the crane joystick needs a high level of skill?
(Apakah anda setuju bahwa bekerja dengan joystick derek membutuhkan keahlian tinggi?)
○ Yes/*Ya*
○ No/*Tidak*
○ Not sure / *Tidak pasti*

9. How do you react during an unpredictable situation?
(Bagaimana anda bereaksi selama situasi tak terduga terjadi?)

………………………………………………………………………………………………
………………………………………………………………………………………………
………………………………………………………………………………………………
……………………………………………………………………………………………

Signed by / *Ditandatangani oleh*: **Date / *Tarikh*:**

END/*TAMAT*

Your cooperation is much appreciated. Thank you.

(Kerjasama anda sangat dihargai. Terima kasih)

Appendix B: The Post-Study System Usability Questionnaire

Objective:
To evaluate the scenario-based usability evaluation for the ROS haptic joysticks prototype by addressing usability characteristics (Lewis, 1995).

Overall, I am satisfied with how easy it is to use this haptic joystick.

Strongly agree	1	2	3	4	5	6	7	**Strongly disagree**	**N/A**

Comments:

1. It was simple to use this haptic joystick.

Strongly agree	1	2	3	4	5	6	7	**Strongly disagree**	**N/A**

Comments:

2. I easily completed the loading, moving, and unloading task using this haptic joystick.

Strongly agree	1	2	3	4	5	6	7	**Strongly disagree**	**N/A**

Comments:

3. I quickly completed the loading, moving, and unloading task using this haptic joystick.

Strongly agree 1 2 3 4 5 6 7 **Strongly disagree** **N/A**

Comments:

4. I felt comfortable using this haptic joystick.

Strongly agree 1 2 3 4 5 6 7 **Strongly disagree** **N/A**

Comments:

5. It was easy to learn to use this haptic joystick.

Strongly agree 1 2 3 4 5 6 7 **Strongly disagree** **N/A**

Comments:

6. I believe I could become productive quickly using this haptic joystick.

Strongly agree 1 2 3 4 5 6 7 **Strongly disagree**

Comments:

7. The haptic joystick gave me feedback that clearly told me how to react to problems.

Strongly agree 1 2 3 4 5 6 7 **Strongly disagree** **N/A**

Comments:

8. Whenever I made a mistake using this haptic joystick, I could recover easily and quickly.

Strongly agree 1 2 3 4 5 6 7 **Strongly disagree** **N/A**

Comments:

9. The information, such as the on-screen messages, and other documentation provided with this haptic joystick were clear.

Strongly agree 1 2 3 4 5 6 7 **Strongly disagree** **N/A**

Comments:

10. It was easy to find the information I needed.

Strongly agree 1 2 3 4 5 6 7 **Strongly disagree** **N/A**

Comments:

11. The vibration pattern as information feedback was easy to understand.

Strongly agree 1 2 3 4 5 6 7 **Strongly disagree** **N/A**

Comments:

12. The vibration feedback was effective in helping me complete the loading, moving, and unloading task.

Strongly agree 1 2 3 4 5 6 7 **Strongly disagree** **N/A**

Comments:

13. The matching of the vibration pattern via the operation situation was clearly differentiated.

Strongly agree 1 2 3 4 5 6 7 **Strongly disagree** **N/A**

Comments:

14. The haptic joystick of this prototype was pleasant.

Strongly agree 1 2 3 4 5 6 7 **Strongly disagree** **N/A**

Comments:

15. I liked using this prototype of the haptic joystick.

Strongly agree 1 2 3 4 5 6 7 **Strongly disagree** **N/A**

Comments:

16. This prototype has all the functions and capabilities I expect it to have.

Strongly agree 1 2 3 4 5 6 7 **Strongly disagree** **N/A**

Comments:

17. Overall, I am satisfied with this prototype.

Strongly agree 1 2 3 4 5 6 7 **Strongly disagree** **N/A**

Comments:

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