Human Factors in Safety Critical Design: Using Haptic Feedback for Robot Teleoperation

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SUMMARY

High hazard industries require the consideration of Human Factors in designing methods to mitigate health and safety risks. Robotic solutions in the nuclear industry can improve operator safety through remote teleoperation, however, for these solutions to be successful the human must be considered. This paper presents a Human Factors review of one of these solutions and has received promising usability results whilst identifying areas for future system development – including improvements to the trolley used to move the robot, and recommendations for a comprehensive training program for familiarisation.

KEYWORDS

Nuclear robotics, teleoperation, glovebox, human factors

Introduction

High hazard industries require strict regulation and compliance to mitigate health and safety risks. Harsh conditions found in many industrial applications can present challenges to human operation. The extreme environments in the nuclear industry for example, often restrict access to facilities due to radiation levels and other hazards. Gloveboxes are windowed, sealed containers that provide primary containment and controlled access to enable operators to manipulate hazardous materials through ports with while wearing protective gloves. The tasks completed within gloveboxes are complex, requiring operator decision making and precision to interact effectively with the hazardous materials. However, there remains a significant risk of exposure to the operator if containment is broken. Serious accidents have occurred in the past, including punctured gloves that resulted in several lifetime doses of radiation (BBC News, 2019).

A solution to this risk for operators is the introduction of robotics into the industry (Bogue, 2011). Robots can remove an operator from dangerous conditions, however, where operator decision making and precision is required, fully automated robots are unsuitable for deployment. Therefore, remote operation, or teleoperation, through haptic feedback has been proposed as an effective means of removing the person from directly interacting with the hazardous materials, whilst retaining their knowledge and decision making to process and interact with these materials.

Previous research has explored this solution of using haptic feedback to control a robot in a glovebox (Tokatli et al., 2021), however, no further work was completed to explore the impact of this type of work on the human. Furthermore, in a review of Human Factors (HF) assessments of haptic feedback hardware, no human factors or usability assessments could be found at the time of writing.

AtkinsRéalis has developed a glovebox solution to minimise radiation exposure, whilst maintaining operator involvement, by deploying a robotic arm attached to a portable deployment platform to complete Post Operational Clean Out (POCO) activities. This solution utilises a Kinova Robot and can be operated both locally and remotely. The robot is locally controlled through the use of an Xbox controller, and remotely controlled using a haptic feedback device. This project, called Risk Reduction of Glovebox Operations (RrOBO), presents an innovative approach for operator safety and participation in the nuclear industry and has ensured HF input through the process to ensure effective and safe deployment. The aim of the assessment detailed in this paper was to gain operator insight on usability of this system. The system involves a bespoke trolley which allows the robot to be moved into the required position adjacent to the glovebox and an Xbox controller for local control to insert the robot into the glovebox port. Once in the glovebox a haptic feedback device is used for remote control of the robot, with two visual display unit (VDU) monitors set up to show the robots movement in the glovebox. The usability of these aspects of the system were reviewed to inform design decisions in the final phase of development prior to deployment.

Method

HF Integration, Operator Trials, and Usability Assessment

Safety is the main goal of the RrOBO project, and human factors input was gained early in the project to ensure ergonomic considerations were accounted for. Once these inputs were integrated into the system, usability and familiarisation trials were conducted. The intention of these trials was to introduce the glovebox operators to the system and identify any difficulties or usability issues that may remain in the design. Furthermore, successful trials may improve the likelihood of acceptance with operators prior to deployment.

Participants

Over the course of three weeks at a nuclear training facility, 11 operators familiar with glovebox operations interacted with the system and completed several tasks designed to replicate existing operational activities.

Procedure

The participants had half of a day to interact with the system under the guidance and supervision of an AtkinsRéalis project engineer. The participants were talked through interacting with the system and how to complete the tasks. They were then observed as they completed the following tasks with the system:

1. Manoeuvring the trolley with the Kinova and deployment platform into place at the workface;
2. Fitting sleeves over the Kinova to allow insertion into the glovebox whilst maintaining nuclear containment;
3. Insertion of the Kinova into the glovebox using an Xbox controller;
4. Using Haption to control the Kinova and completing a set of representative activities.

Teleoperation with Haption involved the completion of tasks that represented POCO glovebox activities. Depending on the task, the Kinova end-effector was changed out from a paintbrush head, to a small gripper and then to a large gripper. The participants used Haption to control the Kinova inside the glovebox during the following interaction activities:

- Paint brush head to push sand across the surface: simulating the clean-up of loose/spilled powder.
- Larger gripper to move blocks into a canister: simulating interior clean-up by picking up and packing items into tubs to be posted out of the glovebox.
- Smaller grippers to move pellets into canister: simulating clean-up of smaller items in the interior.
- Using either the small or large gripper to pick up a wipe and rub the glovebox surface: simulating the cleaning and degreasing of the surface prior to painting fixative, to ensure it adheres properly.
- Paint brush head and latex adhesive: to simulate applying a fixative onto the surface of the glovebox, which then cures and is peeled off, lifting the contamination with it.

There was no time limit on the tasks completed by the participants, they were given the opportunity to interact with Haption to control the robot at their leisure and could progress to the next task when they were ready to. Additionally, the participants were provided with as much support as they needed with the project engineer answering questions throughout the workshop.

Following the trial, each operator was asked to fill out a usability survey to provide information about their experience completing the trial activities. The survey included sections about the overall system, trolley manoeuvring, protective sleeve fitting, local control with the Xbox controller and teleoperation with Haption.

Apparatus and HF System Design Input

The RrOBO system involves the development of a demonstrator using a Kinova Robot arm attached to a portable deployment platform. The deployment platform is a bespoke tool trolley designed to manoeuvre the robot into place.

The trolley was ergonomically assessed with consideration to its weight, handle height and crane controller. A Health and Safety Assessment Risk Assessment of Pushing and Pulling (RAPP) was completed for the trolley and was assessed as not being a risk for the operator, due to its use of caster wheels and weight. The design was anthropometrically assessed using a representative population and including personal protective equipment adaptions from PeopleSize 2020's Visual Anthropometry Software. The height of the current handle bar was raised from 905 mm to 925 mm to reduce possible postural strain from bending forward while moving the trolley and to accommodate a larger population size of both male and female operators.

An Xbox controller connected to the trolley is used for local control and a "Haption Virtuose 6D TAO", is used for teleoperation of the Kinova Robot. The Haption was set up at a remote location with two VDUs for viewing glovebox tasks from two camera orientations. To prevent inadvertent movement of the robot, a foot pedal was used as a safety switch. This switch, known as a "Dead Man's switch," allows the Xbox controller to move the robot only while depressed by the operator.

Analysis

Survey responses were recorded on several 5-point Likert scales to understand the participants' opinions and perceptions towards questions or statements on specific aspects of the demonstrator system or task usability. The participants were then asked to elaborate on these scores, through a qualitative question and text box.

The overall system usability was assessed through a series of statements ranked in agreement, where 1 is Strongly Disagree and 5 is Strongly Agree. Specific aspects of the demonstrator's usability were evaluated. These activities included:

- trolley manoeuvring,
- protective sleeve fitting,
- local control with the Xbox controller
- and teleoperation with Haption.

The usability of the activities above were ranked in terms of:

- Perceived Difficulty (1 is Easy and 5 is Difficult);
- Clarity (1 is Clear and 5 is Ambiguous)
- and Comfort (1 is Comfortable and 5 is Uncomfortable).

The scores answered on the 5-point scale were averaged across all participants for each question and percentages show response distribution. Feedback was also gathered from written responses to open-ended questions and additional detail provided to the questions or statements in in each section. Qualitative responses were assessed by identifying themes, commonalities and critical issues or difficulties.

Results

Participant response rate

The response rate varied from 80% to 100% across survey sections. Approximately two participants completed sections at the front-end of the survey but returned no responses in later sections, this may have resulted from time constraints, or they may have missed these questions.

HF Review

Usability feedback on the overall system was relatively positive after a half-day of introduction, training and familiarisation with the novel system. Table 1 presents the average response determined by the mean score and standard deviation (SD). Participants strongly agreed that technical training and support are needed to use this system. They also agreed that the functions were well integrated, and that the system was easy to use. In terms of learning, complexity, response speed and the effect of user experience; participants were undecided. The majority of qualitative responses to each statement made clear that many participants felt improvements would develop over time with continued use of the system.

Table 1: Overall System Questions

Overall Questions	Average Response	Mean (SD)
Technical training and support are needed to use this system.	Strongly Agree	4.8 (0.63)
The functions in this system were well integrated.	Agree	3.9 (0.74)
Most people would learn to use this system very quickly.	Neutral	2.7 (1.16)
The system is very complicated to use.	Neutral	3 (0.82)

Overall Questions	**Average Response**	**Mean (SD)**
The system is intuitive to use.	Agree	3.6 (0.52)
The system response speed was appropriate for the tasks required.	Agree	3.5 (0.97)
The system is intuitive for users with little to no experience.	Neutral	3.3 (0.82)
The system is intuitive for users with lots of experience.	Agree	4 (0.67)

Trolley Manoeuvring

The responses to questions around trolley manoeuvring varied between positive and neutral with two negative scores. Therefore, this suggests that the participants found their experience of manoeuvring the trolley on average somewhat easy, clear and comfortable.

Table 2 below presents the response distribution by percentage, the mean score and SD for trolley manoeuvring. The mean response of the Difficulty ratings was 1.88 (SD: 1.36), 70% were positive with one person finding it difficult. Participant 1's qualitative response indicated that this was because they found the trolley too heavy and could not see over the top of it.

The mean response of the Clarity ratings ranged from the positive to neutral, with a 70% positive response. The Comfort ratings had a 10% lower level of percentage positive responses, although it should be noted that one participant found it slightly uncomfortable. This person was the same that found the task difficult, due to the weight and size of the trolley.

Table 2: How would you describe your experience with moving the trolley into place?

	1	**2**	**3**	**4**	**5**	**No Response**	**Mean (SD)**
Difficulty	Easy	Somewhat Easy	Neutral	Somewhat Difficult	Difficult	20%	1.88 (1.36)
	40%	30%	0%	0%	10%		
Clarity	Clear	Somewhat Clear	Neutral	Somewhat Ambiguous	Ambiguous	20%	1.75 (0.71)
	30%	40%	10%	0%	0%		
Comfort	Comfortable	Somewhat Comfortable	Neutral	Somewhat Uncomfortable	Comfortable	20%	2 (1.07)
	30%	30%	10%	10%	0%		

Protective Sleeve Fitting

Table 3 below presents the response distribution by percentage, the mean score and SD for protective sleeve fitting. The responses to questions around fitting the protective sleeving varied between positive and neutral with no negative scores. Therefore, indicating a good level of usability and that no difficulty had been brought to the task, which was reinforced by the participant responses.

"(Protective sleeve fitting was an) easy, simple task. Training would be essential, but it was OK."

Participant 7

Table 3: How would you describe your experience with fitting the robot arm into the sleeve?

	1	2	3	4	5	No Response	Mean (SD)
Difficulty	Easy	Somewhat Easy	Neutral	Somewhat Difficult	Difficult	20%	2 (0.76)
	20%	40%	20%	0%	0%		
Clarity	Clear	Somewhat Clear	Neutral	Somewhat Ambiguous	Ambiguous	20%	1.88 (0.64)
	20%	50%	10%	0%	0%		
Comfort	Comfortable	Somewhat Comfortable	Neutral	Somewhat Uncomfortable	Comfortable	20%	2 (0.76)
	20%	40%	20%	0%	0%		

Local Control – Xbox Controller

Table 4 below presents the response distribution by percentage, the mean score and SD for local control with the Xbox controller. There was more of a spread across the responses to Difficulty, Clarity, and Comfort from the participants with regard to local control of the robot using the Xbox controller. However, none were at the negative extreme of the scores.

Two participants found local control with the Xbox somewhat difficult, and their qualitative responses indicated that this because it took time and trial and error to get used to manipulating specific joints with it and understanding the function of each button. This is further reinforced by the participant that found the task ambiguous, they expressed in their qualitative response that it was not evident which joint was selected when changing joints. These results suggest that practice with the Xbox controller is important for acceptance.

"(The Xbox controller) was easy to use once you knew and understood what buttons were used for what on the robot/system."

Participant 2

Table 4: How would you describe your experience using an Xbox controller to manipulate the robot arm?

	1	2	3	4	5	No Response	Mean (SD)
Difficulty	Easy	Somewhat Easy	Neutral	Somewhat Difficult	Difficult	20%	2.38 (1.19)
	20%	30%	10%	20%	0%		
Clarity	Clear	Somewhat Clear	Neutral	Somewhat Ambiguous	Ambiguous	20%	2.63 (0.92)
	10%	20%	40%	10%	0%		
Comfort	Comfortable	Somewhat Comfortable	Neutral	Somewhat Uncomfortable	Comfortable	20%	2 (0.76)
	20%	40%	20%	0%	0%		

Teleoperation – Haption

Responses to questions around teleoperation varied between positive, neutral and slightly negative scores. Therefore, indicating that participants found their experience using Haption neutral in terms of difficulty, clarity and comfort. Table 5 below presents the response distribution by percentage, the mean score and SD for teleoperation with Haption.

The results for the Difficulty ratings mostly vary between positive and neutral, however, two participants found Haption difficult to use. Both qualitative responses revealed that the difficulty they experienced was when they started using Haption, but with more experience and training they found it easier to use.

"The more we used it (Haption) the easier/more comfortable it became."

Participant 6

The responses to the Clarity question revealed that 80% participants found the instructions for using Haption to be somewhat clear or were neutral about clarity. One participant did find the instructions and use somewhat ambiguous. This participant's qualitative response indicated that this was because using the system takes a while to get used to. This reiterates the Difficulty findings and reflects Haption's ease of use. The mean response of the Comfort ratings was 2 (SD: 0.76), 30% were positive and 60% were neutral.

Table 5: How would you describe your experience using the Haption Virtuose to manipulate the robot arm from a remote location?

	1	**2**	**3**	**4**	**5**	**No Response**	**Mean (SD)**
Difficulty	Easy	Somewhat Easy	Neutral	Somewhat Difficult	Difficult	10%	2.67 (1)
	10%	30%	30%	20%	0%		
Clarity	Clear	Somewhat Clear	Neutral	Somewhat Ambiguous	Ambiguous	10%	2.56 (0.73)
	0%	50%	30%	10%	0%		
Comfort	Comfortable	Somewhat Comfortable	Neutral	Somewhat Uncomfortable	Comfortable	10%	2.56 (0.73)
	10%	20%	60%	0%	0%		

Discussion

Given the risks associated with nuclear operations, the safety of operating staff is priority – especially in glovebox activities that have traditionally been more (gloved) hands-on. Therefore, it is important to maintain a human-centred approach in developing methods to mitigate risk. The use of remote handling equipment, such teleoperation of a robot, effectively removes the operator from potential radiation sources. The AtkinsRéalis RrOBO project introduces a robotic solution to improve the safety of the operator in glovebox POCO activities. This paper has detailed the HF review of operator trials introducing RrOBO and presents the findings on usability, initial feedback, and recommendations for further development.

Feedback following the trials were generally positive about the usability of the overall system. Many responses mentioned a learning curve and that most participants picked up how to use the system at some point during the trial, which suggests that time and practice is needed prior to operating. Therefore, the project has recommended that operators required to work with the system are prepared for this with comprehensive training to ensure safe and effective use.

Following the overall questionnaire, participants were provided with questions focusing on the specific aspects on the task, to gather more detail on their reaction to the system. The survey responses to the preparation activities of trolley manoeuvring and protective sleeve fitting revealed good usability as this task was found to be relatively simple and easy to complete. This positive feedback is important as it shows that these tasks have not been complicated by the introduction of the trolley and the sleeve fitting. A suggestion to be considered for improving preparation tasks is to remove or cover the gripper end-effector when fitting the protective sleeving, as the sleeving does not slide over the gripper as easily as other areas of the robotic arm. Negative responses around the trolley's weight and height cannot be addressed at this point due to its requirements for carrying the robot's batteries and the robot unfortunately. However, future developments may see equipment changes that resolve this.

Participants remarked that they found local control using the Xbox controller easy through some practice and trial and error, to understand which button controlled each manipulation. This was to be expected as the Xbox controller is an off-the-shelf product with a high level of familiarity for individuals who play console games. A suggestion to be considered for improving preparation tasks with the Xbox controller is to add some type of indication for joint selection, such as a light, to help the operator identify which joint has been selected during local control with the Xbox controller.

The general sentiment towards interaction activities with Haption reflected the need for a familiarisation phase or learning curve, as well as optimism for continued improvement over time with training and experience. This finding supports a recommendation that time, and support is essential for safe operation and successful deployment of the system.

Future work for this project should look to maintaining system elements that garnered positive feedback and integrating suggestions that arose from neutral or negative feedback. In addition, it would be advantageous to repeat the survey after additional trial session(s) to compare any changes or improvements in feedback. It is advised that these reviews consider and monitor the operators' trust in the system to ensure areas which may lead to a reduction or loss of trust are addressed, promoting continual use of the system. On the whole, it was promising to review positive scores and responses optimistic about the project's potential after such a short period of interaction.

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