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Assessing Tele-manipulation systems using task performance for glovebox operations

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ABSTRACT

Tele-manipulation is indispensable for the nuclear industry, since teleoperated robots cancel the radiation hazard problem for the operator. However, the performance limitations of teleoperated robots for nuclear decommissioning tasks is not clearly answered in the literature. In this paper, we propose a task performance-based methodology to evaluate the performance of bilateral teleoperation of a robotic arm working inside a glovebox. A test based on radiation surveying is designed and the performances of manual task execution and tele-manipulation are compared. Our results show that the current commercial off-the-shelf (COTS) teleoperated robotic manipulation solutions are flexible, yet insufficient, as their task performance is significantly lower compared to manual operation and potentially hazardous for the equipment inside the glovebox. Finally, We present set of rules and solutions, which are deducted from our observations and expert interviews, for better performance in teleoperation in glovebox environments.

Keywords: task performance, bilateral teleoperation, robotic glovebox, robotics, experimental validation

1 INTRODUCTION

Nuclear decommissioning is one of the biggest challenges faced by the nuclear industry and the governments around the world. The UK has the largest nuclear decommissioning and remediation programme in Europe, and the current plan to decommission the legacy nuclear facilities will take a hundred years and billions of pounds (Nuclear Decommissioning Authority, 2021).

Nuclear gloveboxes are an integral part of the decommissioning tasks, where contaminated objects are handled by professional operators. In glovebox operations, the radiation hazard for the operator is lowered but not completely eliminated. In a few occasions, operators were exposed to radiation as a result of an accident that happened in the glovebox (Rollow, 2000; Hagemeyer and McCormick, 2012; Cumbria, 2019). The risk of accidents forces operators to adopt strict operational measures. Moreover, the gloveboxes are unergonomic by their designs, and as a result, working in a glovebox is a strenuous job for the operators.

There are various challenges in nuclear decommissioning, and gloveboxes are identified as a case study for implementing robotic technology for manipulation by 2025. While the goal is to implement a bilateral teleoperation system for performing some of the decommissioning tasks in a glovebox, the current vision is to take over 50% of the glovebox operations from human operators by 2030 (Nuclear Decommissioning Authority, 2021).

Teleoperated robots offer safer manipulation in hazardous environments by keeping the operators away from radiation sources, and they allow operators to continue working on their tasks without being limited by the levels of the exposed radiation. Moreover, teleoperated robots with assistive control techniques can potentially improve the performance in decommissioning tasks. However, despite the common use of robotic teleoperation in nuclear applications, the performance levels of bilateral tele-manipulation systems are not clear and often difficult to measure.

Understanding the task performance in tele-manipulation is crucial for designing better and more capable robotic systems for nuclear decommissioning. However, evaluating the performance could be challenging since comparing two different manipulation methods faithfully cannot always be achieved by objective metrics; especially when the human is involved in the manipulation process. Therefore, objective measures and subjective assessments should be used coherently to understand the task performance. To the best of our knowledge, there has not been a systematic task performance assessment of teleoperated robots used in nuclear sites. The aim of this paper is to open a new perspective on understanding the performance offers of teleoperated robots in nuclear operations.

In this study, manual object manipulation, *i.e.* using hands directly for manipulating objects, is assumed as the most intuitive and easy to use manipulation method for humans, and it is treated as the ground truth for our study.

In this paper, a methodology based on task performance is proposed to compare tele-manipulation and manual manipulation using as case example radiation survey. The goal of the study is to investigate the advantages and disadvantages of both manipulation methods. Authors have hypothesised that due to factors such as lack of sensory information and the use of unintuitive kinematic structure of the local (master) device, the performance of robotic tele-manipulation is worse than manual manipulation, and it causes higher cognitive load on the operator.

The paper is organised as follows. In Section 2 the related work on the problem of evaluating the performance in teleoperated robotics is presented, in Section 3 the experimental setup, the design of the experiment is presented, and performance metrics are explained. Section 4 presents the results for the experiments, and Section 5 provides a discussion of the results. Finally, Section 6 concludes the paper.

2 RELATED WORK

2.1 Performance in tele-manipulation

Performance in teleoperated robotics have been investigated in two groups: system performance and task performance. The device performance is the quantitative analysis of the robots used in the tele-manipulation. Despite the importance of the manipulation interface, system performance can tend to omit the assessment of the operator. Therefore, in this paper, we are going to focus on the task performance where the user, device and the task execution are evaluated simultaneously.

The literature on teleoperated robots have a wide spectrum of task performance analysis; however, comparing tele-manipulation to manual manipulation has drawn less attention. Richard et al. (1999)

considered the performance in pick-and-place task for teleoperated robots with different feedback modalities and manual task execution. In order to obtain reproducible results, the teleoperated system was implemented in a virtual environment and the operator used a haptic interface for manipulation. It was shown that task completion time and accuracy were better in manual manipulation, whereas force feedback improved the accuracy in teleoperation.

In a different application area, task performance of teleoperated robot and manual manipulation was given in (Li et al., 2000). Experienced surgeons were asked to perform a suturing using conventional open surgery, with laparoscopic tools and, finally, with teleoperated surgical robot. It was shown that, suturing with teleoperated robots took longer to complete compared to conventional methods with higher leakage rate. However, it was found that teleoperated robots were providing better performance than laparoscopic tools due to the lack of fulcrum effect.

Motor skills play a key part in manipulation, and being able to assess the human motor skill capability is an important measure of the task performance. Geiger et al. (2010) had developed a new test bed for assessing the fine motor skills with teleoperated robots. The aiming, finger dexterity, manual dexterity and wrist-finger speed were evaluated. It was found that, compared to human hand assessment, teleoperated robots increase completion times. Moreover, finger dexterity, aiming and manual dexterity had a stronger negative influence by the teleoperation system.

In the context of this paper, teleoperation with dissimilar kinematics is an important concept to understand. In this teleoperation setting, the master and slave robots have different kinematic and, possibly, dynamic characteristics; therefore, the control modality for this type of teleoperation differs from the control modality of similar kinematics teleoperation. In Ben-Porat et al. (2000), task performance analysis with dissimilar kinematics was investigated for a surgical application. The authors had investigated the placement of the master robot and the visuo-motor mapping of the remote environment. It was found that master robot placement has a direct effect on the task performance. Moreover, it was shown that simplifying assumptions on complex tasks could give misleading results on the actual task performance.

Another study which focused on the effect of force feedback on task performance is Wagner and Howe (2007). The performance of a teleoperated robot for a surgical task was evaluated. It was found that the force feedback reduces the forces applied in the remote environment. It was, also, found that force feedback reduces the completion times for trained surgeons; but, novice users did not benefit from the haptic feedback.

In Yip et al. (2011), the task performance is evaluated for a simple peg-in-the-hole with time delay in the force signal. Different teleoperation modalities were evaluated: unilateral, bilateral and no force feedback with various time delay levels were considered. It had been shown that time delay increases the task completion times regardless of the teleoperation modality. Force feedback reduced the force applied on the remote environment.

2.2 Robots in gloveboxes

Using robots for glovebox operations has long been an interest for the robotics community (Grasz and Perez, 1997; Pedrotti et al., 1991). Akiyama (1996) used a robotic manipulator as an early example of robotic decommissioning, where the robot is used to dismantle the JDPR reactor. An autonomous robotic system is proposed in (Harden et al., 2009) for reducing the radiation hazard for the operator and improve the safety. Similarly, robotic systems are proposed for reducing operational costs (Pegman and Sands, 2006; Peterson, 2000).

Redundant manipulators have been extensively used in gloveboxes for improving the manipulation capability inside the contained space. In Turner et al. (2001), a redundant manipulator is used to avoid collisions with the environment. Another use of redundant manipulators in gloveboxes include improving the manipulation (Roa and Suárez, 2015) for robust handling of objects.

The glovebox operations are physically demanding for the operators who are exposed to radiation hazard. Therefore, not only the operator safety is in question; performance limitations in glovebox operations pose a challenge on their own. Despite extensive training aimed at improving the operator's skills for executing glovebox operations, robotic systems have been shown to provide assistance to operators (O'Neil, 2010). Ghosh et al. (2020) investigated the use of high-level voice commands to humanoid robots which are designed to work in legacy gloveboxes. Finally, other robotic applications for gloveboxes include the use of humanoid robots (Onol et al., 2018; Long and Padir, 2018) and continuum robots (Lastinger et al., 2019) to help perform maintenance tasks in constrained environments such as a glovebox.

3 EXPERIMENTAL PERFORMANCE EVALUATION

An experimental approach was used to understand and evaluate the performance of bilateral tele-manipulation for glovebox operations, considering task-performance as its main component. For this, we first selected a representative task performed in glovebox operations, then we created a parametrizable test based on the task itself, to be applied under different manipulation methods (i.e., manual operation or tele-manipulation). Performance metrics were derived based on expected timings, accuracy and possible effects that unplanned interaction with the glovebox would provoke (e.g., unplanned collisions with the glovebox, cross-contamination).

The task for the experiments is selected as radiation surveying, which is common in many glovebox operations and often performed by trained operators. In this work, we refer to tasks as a sequence of operation-relevant activities that are performed during a glovebox operation (e.g., opening and closing a sealed container are tasks performed during a maintenance operation). Therefore, the experimental evaluation does not focus on basic actions such as grasping or moving an object from one location to the next, as these could be construed as building blocks of a task performed in a glovebox operation.

This general methodology can be adapted to other tasks. However, our results should be indicative of the expected performance whilst performing other tasks for the same tele-manipulation system, as most tasks performed inside a glovebox face the same limitations (i.e., use of tools to interact with substances whilst suffering from poor visibility and dexterity).

3.1 Radiation Surveying in Glovebox Operations

In the context of glovebox operations, the radiation surveying is a task performed to know the levels of radiation of any potentially contaminated object or area. It is usually performed by using a handheld sensor (probe) connected to a ratemeter outside the glovebox. The sensor's response to ionising radiation, such as alpha and/or beta particles, is dependent on its distance from and relative orientation to the source. The main difficulties faced by trained operators whilst performing radiation surveying are around manipulating the handheld sensor at a constant distance to the source while slowly moving the probe to avoid collisions as it could damage or contaminate the probe. Moreover, the operators perform radiation scanning while wearing multiple layers of protective gloves, under reduced mobility and dexterity due to the limitations of the glovebox and under reduced visibility of the tinted glasses of the glovebox which makes it difficult to estimate the clearance between the probe and the source.

Radiation surveying tasks can be classified in two groups: (i) an operator surveying a visible object (Object Radiation Surveying) and (ii) an operator discovering potential radiation sources or contaminants in the glovebox (Workspace Radiation Surveying). Object Radiation Surveying is often the main focus of glovebox operations, where an object of unknown levels of radiation is taken out of its specialised container and surveyed to understand its level of degradation over time. Workspace Radiation Surveying is a task where the interior of the glovebox is surveyed to identify residual levels of radiation.

Nuclear gloveboxes are *active* work environments, as they are regularly used for decommissioning and maintenance tasks. As a result, particular areas and surfaces in the glovebox can become active with residual levels of contaminants. To contain the contamination and minimise the radiation hazard, the Workspace Radiation Surveying has to be securely and reliably conducted by the operator.

3.2 Radiation Surveying Testing Protocol

3.2.1 Test Description

An experiment was designed based on Workspace Radiation Surveying, as defined in Section 3.1. A repeated measures experimental design was used to quantify and measure task performance of two manipulation methods (manual operation and tele-manipulation), as seen in Figure 2a.

In the experiments, the test subject looked for an unknown simulated radiation source inside the glovebox workspace and reported it to the experimental officer. The glovebox workspace was defined as a 30 x 40 cm area, and segmented in sectors of 10 x 10 cm, as seen in Figure 1. Each participant repeated the task four times, with each iteration being timed and their answers recorded. The number of contaminated sectors was unknown to the test subject, and it varied from one to four tiles per iteration. The glovebox workspace was located in front of the glovebox's glove port for manual operation and inside the robot's workspace, as seen in Figure 2b.

An STS Ionizing Radiation Simulator System was used to simulate a contaminant on the glovebox workspace being detected by a probe. The DP6-RE Simulated Probe (STS Ltd, 2022) and the Thermo RadEye SX radmeter were used with the LS1 Liquid Simulated Source, which produces a gas when in contact with the air that the probe identifies as ionizing radiation. The radmeter alerts the user of changes using its display, a red LED and a sound alarm. The LS1 Liquid was sprayed on tiles placed in any of the sectors of the glovebox workspace, changing its location in-between tests. The DP6-RE Simulated Probe was fitted with a gripping block that enables a robot to grasp it easily. This equipment is used to train operators in cross contamination and decontamination exercises, as it simulates the size and behaviour of a real probe (i.e., needs to be moved close to and slowly over a surface).

The experiment began with a general explanation of the task to perform, the sensors and measurements taken during each trial, and a short familiarization stage with the simulated radiation sensor and the robotic manipulation method. Test subjects performed the task manually and then switched to using the tele-manipulation setup (see Section 3.2.3). At the end of the experiment, a NASA-TLX test (Hart and Staveland, 1988) was administered, and a short interview was conducted, to understand the view of the participant on the preferred manipulation method.

3.2.2 Test Subjects

Test subjects were recruited from a pool of individuals working or associated with the Remote Applications in Challenging Environments (RACE) of the United Kingdom Atomic Energy Authority (UKAEA). The recruitment process primarily focused on research engineers working in the area of

1	2	3	4
5	6	7	8
9	10	11	12

Figure 1. Physical layout for radiation surveying test.

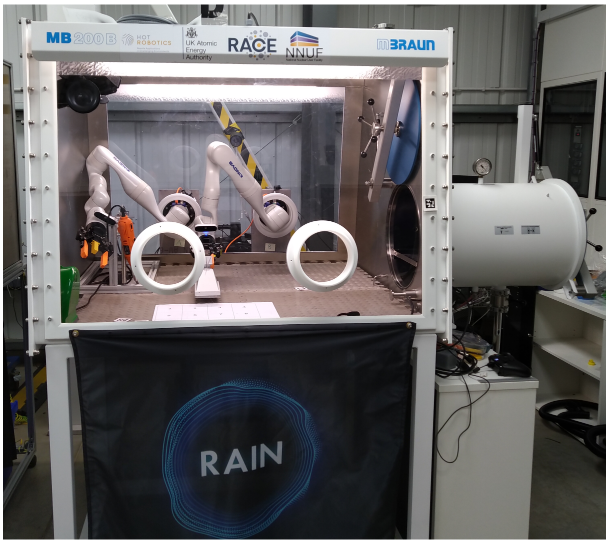

Figure 2a. Glovebox used for experiments. The remote environment is manipulated using a Kinova Gen3 robotic arm.The glove ports are used for accessing the glovebox interior.

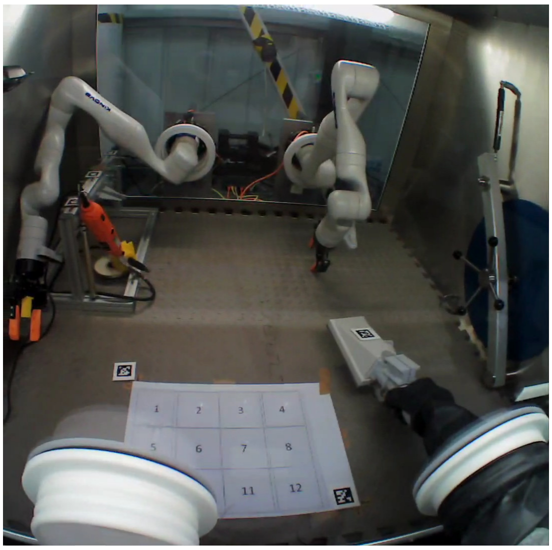

Figure 2b. The glovebox workspace during experimental trials. The grid is placed closer to the operator and robots are turned off during manual manipulation trials.

teleoperated robots and remote handling operators who are experienced on remote maintenance tasks inside gloveboxes or in similar environments. Moreover, experience on robotics was required for the participants and the participation in the experiment was not imposed on the test subjects as a requirement for their continuous employment. All health and safety requirements were met to operate the devices, and risk assessments were prepared for operating all the equipment used in the experiment. The national guidelines for close contact with test subjects were followed during the experiment. No ethical approval was required as no personal, sensitive or confidential data was acquired, with consent given by the participants. The data recorded during the trials were anonymised, kept away from third parties, and the participant views expressed in the interviews were not shared with anyone outside the authors of this work.

3.2.3 Manipulation Methods

In the experiment, two different manipulation methods were used to assess the operator performance in the radiation survey task described in Section 3.2.1.

3.2.3.1 Manual manipulation

A radiation probe for measuring the (simulated) radiation level on a surface was used by the subject, who was told to use their dominant hand whilst wearing a pair of protective gloves. Figure 2b captures an exemplary trial with a subject using the probe on the grid given in Figure 1.

3.2.3.2 Tele-manipulation

In the experiment, a commercial off-the-shelf bilateral tele-manipulation system was used to perform glovebox tasks. On the remote side, the tele-manipulation system consists of a Kinova Gen3 robotic arm with 7 degrees-of-freedom (DoF), mounted with a Robotiq 2f-85 parallel jaw gripper with modified fingers. The remote robot was fixed to a pedestal outside the glovebox and fed into the glovebox through the existing glove port, as seen in Figure 2b. The Kinova Gen3 robot has been used to develop a robotic glovebox (Tokatli et al., 2021), as they are low-cost and of ideal size to fit through the entry port of most gloveboxes.

The local side of the tele-manipulation system is a Haption Virtuose™ 6D haptic interface (Garrec et al., 2004). The haptic interface allows intuitive control of the remote robot's end-effector, with buttons on the haptic interface assigned to adjust the remote robot's elbow configuration using the nullspace projection in its inverse kinematics. The test subjects held the haptic interface 0.5 m away from the glovebox itself, with a clear view over the workspace as seen in Figure 3.

The choice of this particular teleoperation setup is based on its availability. The Haption Virtuose haptic interface is a commercial solution which is being adopted in many teleoperation and remote handling applications, and provides high force feedback in 6 DOF with out-of-the-box integration with many robots, including the Kinova Gen3 robotic arms. The control system and the inverse kinematics of the tele-manipulation system were used as supplied by the vendor.

Figure 3. Test subject operating the Haption device to perform radiation surveying.

3.2.4 Sensors and Performance Metrics

In order to identify the task performance of each subject, three task performance metrics are defined.

- *Task accuracy* which is identifying the cell number(s) contaminated with simulated radiation
- *Completion time* which is measured in seconds

- *Number of detected collisions* which are between the sensor and the environment

The performance metrics are designed considering the objective of a radiation surveying task. A successful radiation survey should identify the hot spots in the environment without previous knowledge and, during the surveying, the probe and the potentially contaminated surface should not collide.

In addition to the performance metrics, additional sensory information were gathered during each experimental trial to understand both the robot and human behaviour during each trial and how these change per manipulation method. Three video feeds were recorded with a timestamp overlay to aid analysis, two from the inside of the glovebox (side and top view) and one of the test subject whilst performing the task. Eye tracking glasses were used (Tonsen et al., 2020) with fiducial markers on the scene to record gaze patterns and compare them between manipulation methods. Additional data was recorded during tele-manipulation from the local and remote robots at 1 kHz sampling rate.

3.3 Hypothesis

It would be expected that an appropriate teleoperation method allows for a task being performed similarly or better than done manually. However, we expect that compared to manual operation, tele-manipulation would make a task take longer due to it being harder to control.

4 EXPERIMENTAL RESULTS

Experiments were conducted as described in Section 3.2. Seven test subjects participated in the experiment, six of them being trained remote handling operators and one novice user. All the test subjects had experience with robots and teleoperation systems, such as MASCOT (Hamilton and Preece, 2001). All the test subjects had training and experience using the haptic device and had a familiarization period with the robot holding the sensor probe. All the test subjects managed to perform the radiation surveying task using both manipulation methods (i.e., they manipulated the sensor probe and found contaminants in the glovebox workspace). Only one iteration of the test had cross-contamination of the probe (i.e., the probe was in direct contact with the LS1 Liquid), leading to resetting the test after appropriately cleaning the probe; this instance occurred during one tele-manipulation trial. The task metrics introduced in Section 3.2.4 were used to compare task performance between manipulation methods with a two sample t-tests (Delacre et al., 2017).

The number of recorded crashes was significantly larger whilst using the local device of the tele-manipulation system, having on average 4 crashes per trial, as seen in Figure 4. This difference is statistically significant with $p = 2.98 \times 10^{-6}$. Another important note is the number of crashes in a trial equal or higher than six were reported as six.

Figure 4 depicts the completion time in trials, where the duration for each trial was significantly longer and more inconsistent whilst using the tele-manipulation system. On average, the manual operation took $96.11\,\mathrm{s}$ whereas the tele-manipulation system took $199.36\,\mathrm{s}$ to complete a trial. This difference is statistically significant with $p = 2.95 \times 10^{-5}$ reported from a two sample t-test with unequal variance, *i.e.* Welch's t-test, (Delacre et al., 2017).

Regarding the accuracy, both false positives and missed sectors were significantly higher during tele-manipulation, with a notable difference on the latter as no missed sectors were reported during manual operation. Figure 5 shows the number of false positive sectors reported per trial, with on average 1.82 sectors badly reported during the tele-manipulation against 0.75 during the manual operation; this is a

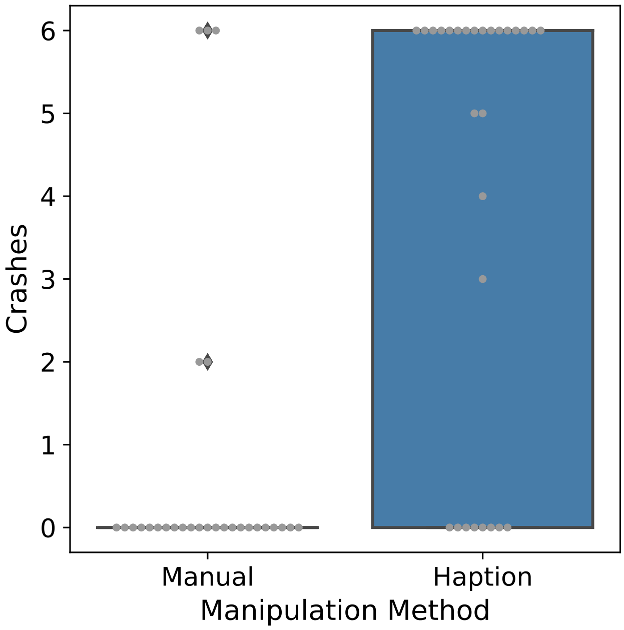

Figure 4. Boxplot with overlaid beeswarm plot comparing the number of probe collisions with the glovebox floor per trial whilst performing radiation surveying.

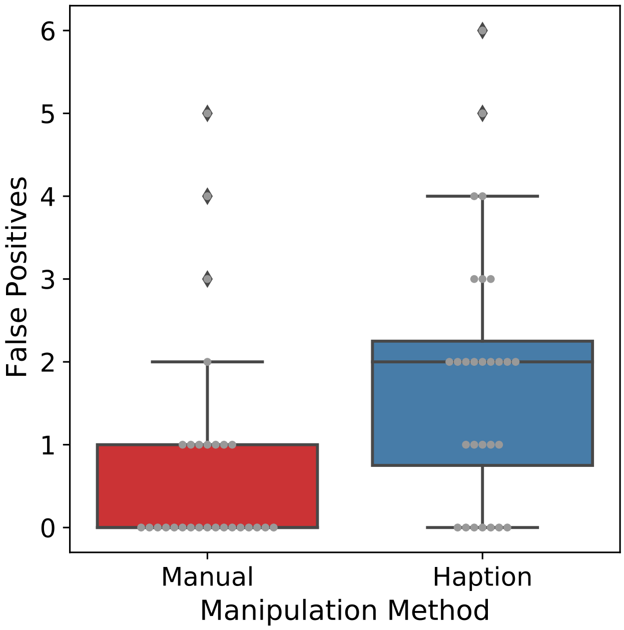

Figure 5. Boxplot with overlaid beeswarm plot comparing the number of false positives reported by test subjects per trial.

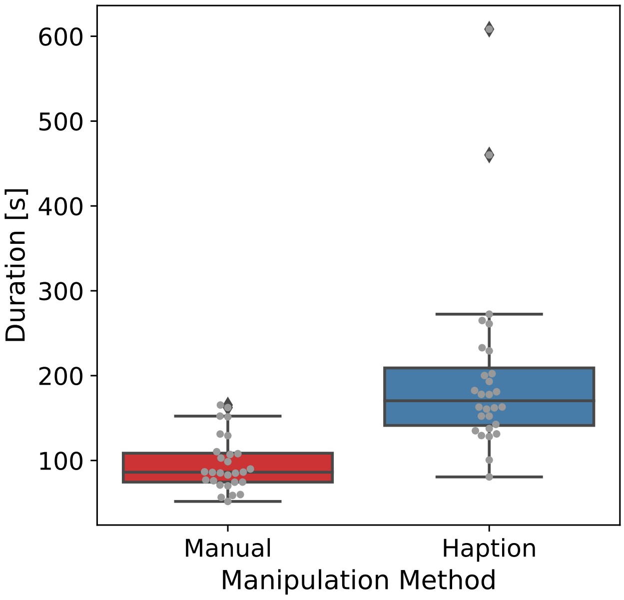

Figure 6. Boxplot with overlaid beeswarm plot comparing duration per trial.

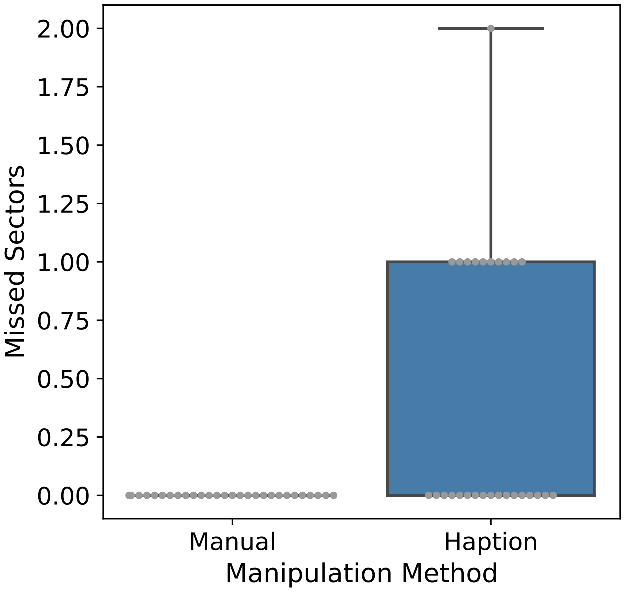

Figure 7. Boxplot with overlaid beeswarm plot comparing the number of contaminants not reported per trial.

statistically significant difference with $p = 0.007$. In contrast, Figure 7 shows the number of contaminated sectors that were not reported during trials, with 0 reported during the manual operation against 0.42 during the tele-manipulation on average; this difference is statistically significant with a $p = 0.0004$ reported from a two sample t-test with unequal variance, *i.e.* Welch's t-test.

The subjective experience from test subjects using the tele-manipulaiton device when compared to manual operation was recorded using the NASA TLX test. Figure 8 summarises these findings, with large variation between test subjects in the Frustration, Mental Demand and Physical Demand factors; although the group average for these factors is a medium value (i.e., NASA TLX is reported in a range from 1 to 20), many test subjects reported other values that make it difficult to make conclusions from these factors. Temporal Demand and Performance show less variability and low average values, meaning most test subjects did not feel pressed or rushed to finish the task using the tele-manipulation system compared to manual operation. However, most test subjects reported high values in the Effort factor (12 in average), which can be interpreted as the test subject having to put significantly more effort to perform radiation surveying in the glovebox using the tele-manipulation system.

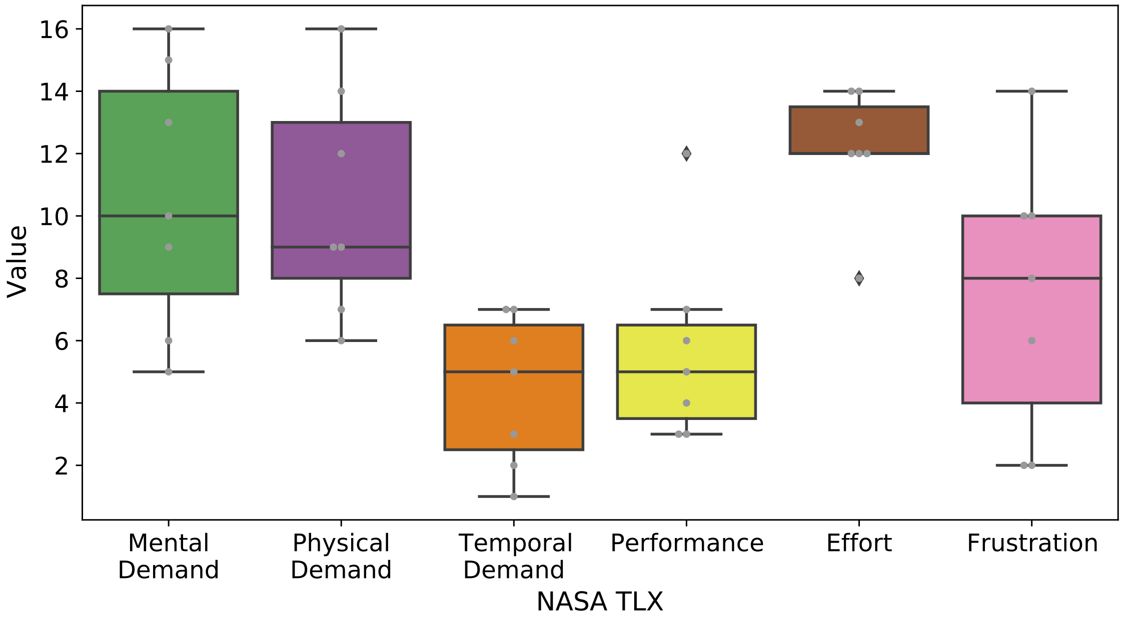

Figure 8. Boxplot with overlaid beeswarm plot of the reported NASA TLX results.

Although there were not enough novice test subject in our study to draw statistically significant conclusions, task performance was not significantly worse off for the novice test subject compared to expert operators. All trials took longer than the group average (above 260 s against 199.36 s), with half of the trials taking longer than 300 s; however, the number of crashes, false positives and missed sectors were similar to other test subjects. This was expected due to the difference in expertise using both teleoperation devices and performing radiation surveying.

There were no relevant performance improvements over trials per test subject (i.e., task performance did not improve steadily with repetition). Test subjects reported feeling more comfortable with the tele-manipulation interface and there was no significant improved, meaning the duration stayed above the 100 s and there were occasional crashes and missed detected sectors.

Regarding gaze patterns and engagement with the task being performed, all test subjects focused on the scanning task using any of the manipulation methods (i.e., keeping fixation inside the workspace and around relevant equipment). A raster scanning patterns was seen in most test subjects, going side to side and changing rows one sector at a time. Fixations were either an onset of the sector to be scanned

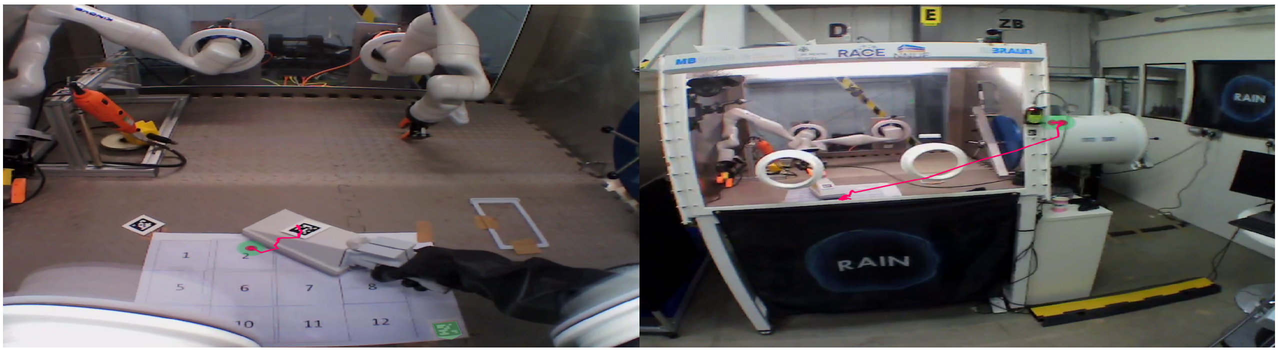

Figure 9. Example of fixations (green dot) and gaze patterns (purple lines) whilst performing radiation surveying using manual operation (left) and tele-manipulation (right).

next or pursuing of the probe as it moves. Besides workspace fixations, the radmeter was consulted to verify a contaminant being detected; however, most test subjects relied on the sound alarm produced by the radmeter alone and kept focus on the workspace, except for the novice user. Figure 9 shows the fixations and motion between fixations for a manual operation and a tele-manipulation trial, with the latter mimicking the manual operation until a contaminant was found. Other fixation points during trials were only seen during tele-manipulation, which were the Kinova second joint and the haptic device itself. Five out of seven test subjects changed gaze from the glovebox to the dials and controllers in the haptic device, either to use the redundancy buttons or to confirm grip and grasp inputs; three test subjects had to look at the haptic device in three trials, one on two trials and one during a single trial alone.

4.1 Remote Handling Operator Interview

After completing the trials, the JET remote handling operators were asked the following questions, indicated with **Q**, and the answers to the interview questions, indicated with **A**, are summarised below.

Q The teleoperation system has haptic/force feedback for the teleoperator. Were you aware of the haptic feedback during the experiment? If you were aware, did you find it useful for completing the task? Why?

A All interview participants except for one indicated that they were aware of the force feedback in the bilateral teleoperation system. The majority of the answers clearly stated that they felt the weight of the sensor. All answers indicated that the force feedback is useful for the tele-manipulation.

Q You have experienced two different manipulation methods for gloveboxes. Which method would you prefer if you were given the chance to select? Please do not take the radiation hazard into account when answering the question.

A All interview participants except for one preferred manual manipulation over tele-manipulation because it was considered more intuitive, quicker and easier. One participant thought that manual manipulation is more exhausting, and the participant finds tele-manipulation easier to use.

Q Do you think that, from a user's perspective, the teleoperation system can be improved? How?

A 3 answers suggested using teleoperation system with similar kinematics as the robots. 2 answers highlighted the importance of the relative positioning and orientation of the local and remote robots. 2 answers reported that the inverse kinematics algorithm used in the teleoperation systems should give more intuitive joint configuration. 1 answer commented on improving the clutching mechanism of the teleoperation system for a smoother transition after releasing the clutch. 1 answer suggested using auditory or visual feedback to the operator in case of reaching the limits of the physical workspace of the haptic interface. 1 answer suggested having higher fidelity in force feedback so that touching the remote environment with the sensor could be perceived by the operator. 1 answer suggested having a force scaling mechanism where heavier objects are felt lighter on the operator side.

Q What was the most challenging part of the manual manipulation?

A The answers were around the physical limitations imposed by the glovebox. This is either working in a limited working area, reduced reaching capability or carrying a heavy object (i.e., sensing probe) for prolonged time in uncomfortable body positions.

Q What was the most challenging part of the tele-manipulation?

A The answers highlight that understanding the foreign kinematic structure of the local and remote robots was the most challenging part of the tele-manipulation. Related to this issue, one interview participant highlighted the importance of training for the setup. With training, the operators are expected to develop better intuition on how the remote robot moves. In this context, the elbow motion of the remote robot as a result of the redundancy was identified as an important problem of the manipulation system. The limited workspace of the local robot compared to the remote one was identified as another limitation of the system. Moving the remote arm without colliding with the remote environment was considered as easy as they expected. Finally, interviewees stressed out the relative orientation of the local and remote robots.

5 DISCUSSION

As seen in Section 4, there is substantial evidence to support the claim that task performance during tele-manipulation was considerably lower compared to manual operation. Although one might argue that it is not fair to compare the task performance of any teleoperation system or device with manual operation, it is necessary to adopt manual operation as the ground truth or basic performance that any future robotic system should achieve or outperform. The tele-manipulation system provided a flexible and effective haptic-enabled control of the robot's end effector, but task performance was not ideal even when used by trained operators. A task-aware technical analysis is necessary to understand the reasons behind these results and ways to improve them. The next step is to analyse the results, provide our hypothesis for why task performance was so dissimilar, and propose solutions for future teleoperation systems.

The largest factors affecting the teleoperation performance are the same that define any task performed inside a glovebox: the interplay between the limitations of the manipulation method, environmental constrains and tool characteristics. First, the glovebox is a restricted space, with visibility only available from shaded glasses placed in one side of the box. In addition, the sensor used during the trials is a realistic training probe that weights 0.9 Kg, which was even reported as heavy during manual operation by some test subjects. Furthermore, the Kinova Gen-3 robot has a redundant joint (elbow joint) that allows to reach many end-effector configurations by rotating the redundant joint close to kinematic singularities, leading to potential collisions between the joint and the glovebox limits.

The large number of probe collisions were primarily due to the reduced depth perception inside the glovebox, which complicates the test subject's task of estimating distance between the probe and the floor; this estimation is crucial whilst moving the probe, as optimal radiation surveying requires constant distance and orientation relative to the floor. The weight of the sensor probe and the robot's joint configuration necessary to use the sensor lead to further control difficulties. When starting control action from the haptic device using the enabling clutch and the dead man's switch, a sudden and unplanned drop in the end effector's position occurred the closer the probe was to the floor, sometimes leading to crashes against the floor. Although the weight of the sensor is well within the robot's reported 2 kg full-range payload, it is theorized that the cantileaver-like configuration required to operate the probe (see Figure 2a) is particularly challenging for the haptic device's commercial weight compensating torque controller. All these translate to reduced dexterity, with big effort needed to stabilize and operate the haptic device, as reported in the NASA TLX at the end of Section 4. It could be argued that by redesigning the sensor probe or the gripping block to allow the sensor to be grasped and manipulated from a different angle (i.e., vertical orientation instead of a mostly horizontal) would help, but these Ad-hoc solutions would restrict the robot's workspace, its usability and incur redesigning costs.

The situations explained below can also explain the low accuracy experienced during tele-manipulation (i.e., large number of false positives and missed sectors). Low dexterity makes it difficult to differentiate one sector from the next, as the probe requires slow and stable movements parallel to the glovebox's floor.

It is worth noting that both collisions between the probe glovebox, and contaminants not found are not acceptable during any radiation surveying task. Although short surveying times and no false positives are desired, long and over estimating survey are safer and more desired than surveys damaging the sensor probe or missing dangerous contaminants.

The interviews with professional remote handling operators revealed interesting design pointers, and help researchers to have a better understanding on the expectations from industry professionals.

The answers of remote handling professionals reflect their experience with the JET remote handling system, and they are inherently biased to favour this system over other tele-manipulation system. Their comments on force scaling and similar kinematics reflect this preference. However, this bias is not something researchers should ignore. On the contrary, the suggestion from the interviews on having a similar kinematic structures for both local and remote robots improves the operational safety and easy of use of the tele-manipulation system. Being able to control each link of the remote robot is crucial in this context.

The existence of force feedback is appreciated by the operators; however, as pointed out in an answer by an interviewee, the force rendering fidelity of the selected COTS teleoperation system did not allow operators to feel low amplitude contact forces; hence, force feedback was not utilised to secure a collision free course for the radiation sensor. On the contrary, all operators relied on their vision to detect collisions. We deduce that transparency of the tele-manipulation system is crucial for safe operations and, in this particular case, agility of the operator. This hypothesis needs further evaluation.

Using a robot with different kinematic structures offers advantages such as reduced cost. However, the inverse kinematics algorithm becomes crucial for such tele-manipulation systems. In the presence of redundant manipulators, the inverse kinematics could significantly degrade the performance by causing redundant elbow motion. This phenomenon was detected by the participants and identified as a problem of the tele-manipulation system.

One participant identified an important problem regarding the haptic interfaces. As the operator is mentally engaged with the remote task during teleoperation, there is no way to distinguish the end of the physical workspace or a collision in the remote environment. In both situations, the haptic interface resists to the motion of the operator. This situation creates confusion on the operators, and we argue that it increases the cognitive load on the operator.

Considering the problems showed during tele-manipulation using an advanced commercial solution, we present a list of key features and improvements necessary for control interfaces used in radiation surveying and other glovebox maintenance tasks:

- Cartesian motion and velocity compensation to move at a fixed distance from a surface whilst holding a fixed orientation.
- Surroundings-aware kinematics, avoiding both collisions between the joints and the glovebox and the probe with the glovebox floor.
- Introduce a constant-torque mode for the Haption device, which compensates for the payload weight and holds the robot's end-effector position between activations.

6 CONCLUSION

A methodology to compare tele-manipulation methods in a glovebox environment was presented, by using a radiation surveying task and different performance metrics. Task performance was measured for the tele-manipulation system compared to manual operation whilst using an ionizing radiation simulator systems used in the industry. A Haption Virtuose™ 6D TAO Virtuose controlling a Kinova Gen3 arm was shown to be able to perform radiation surveying by teleoperation; however, measured task performance was significantly lower compared to manual operation. A list of reasons and solutions to these problems were presented. We managed to show the shortcoming of current off-the-shelf commercial offering for glovebox operations, as current iterations of these systems as still not sufficient to replace manual glovebox operations.

When faced with constrains in technical challenges, it is easy to advocate for a complete redesign or change in the equipment used (i.e., robot, glovebox and sensor). However, these experiments exemplify the current challenges faced by robotic glovebox operations and systems, as robust and flexible solutions are needed that fit both legacy equipment and build towards the robotic gloveboxes of the future. By implementing and measuring a relevant maintenance task involving tool handling and a defined workspace similar to what an operator would face in manual operation, relevant comparisons and limitations can be seen in teleoperation interfaces.

Future work includes testing more test subjects from both expert and novice background and creating a human robot interface (HRi) that implements some improvements described in Section 5, namely limiting end-effector motion to a plane at a certain distance from the floor.

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