Enhancing the Intuitiveness of Remote Mobile Industrial Robots with Haptic Devices

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Abstract

This paper presents the potential integration of Haptic Devices to complement the current Virtual Reality interfaces used for a remote mobile industrial robot. The integration of haptic feedback devices provides proper kinaesthetic awareness to operators, facilitating a feeling of total immersion, as if physically present. The ability to touch and feel, provided by these devices, allows for greater dexterity when operating these robotic systems. It can also solve issues when working within fragile and precision-required environments where current forms of remote teleoperation are lacking. A summary of the teleoperated manipulator, controlled by a haptic device, is outlined in this paper. This system is tested, and the findings from a human user study using the examined control method are presented. The human user study explores the effect of varying environments and modes of visual feedback on the participants' performance. These results demonstrate the most practical form of visualising an unknown environment when leveraging haptic force feedback.

1 Introduction

1.1 Motivation

Rock scaling is frequently used within the mining industry as a method of mitigating risk to people and structures through "the extraction of loose earth from a rock face by using hand tools, explosives and other mechanical processes" [1][2]. This practice also allows for increases in mining-related operations as it is frequently used in mines to create safer and more stable working environments [3]. However, fundamental issues lie inherently with the technique of rock scaling. The process by nature, is dangerous and suffers from a lack of available labourers [4]. Furthermore, rock scaling is often unpredictable, with incidents of rocks falling without providing any obvious signals before a potential incident occurring [5][6].

One solution for robotic feedback in rock scaling robots that is currently being heavily researched is the field of virtual, augmented, and mixed reality (VR, AR, MR) [7][8]. A research study has demonstrated the feasibility of visual feedback systems utilising a VR workspace to control robots [7]. These technologies provide an interface where operators immerse themselves within a simulated environment that facilitates effective control for teleoperated systems. These interfaces provide users with real-time immersion, improving their understanding of the working environment [9].

The paper concludes that the VR-based control interfaces allow intuitive control of real-world robotic manipulators over traditional methods using game controllers or teach pendants. These contrasting control methods were compared by analysing participant task performance [7]. Despite the large potential of solely VR visual feedback systems, using purely a visual form of feedback has limitations when attempting to achieve delicate objectives within fragile locations [10]. This issue may be addressed by applying haptic feedback in combination with this enhanced visual perception method. The interactive effect and combination of these sensing modalities will be explored in this paper.

1.2 Literature Review

Haptic force feedback refers to the sense of touch. It allows humans to perform various tasks, such as physically touching, grasping and manipulating objects within their working environment [11]. Kinaesthetic sensations are an integral part of haptic feedback and provide humans awareness of their body position in space, relative to other objects. In the case of haptic devices, this is conducted through a multitude of forces, torques exerted onto the user through the device. These forces can express the sensation of the surface of an object and

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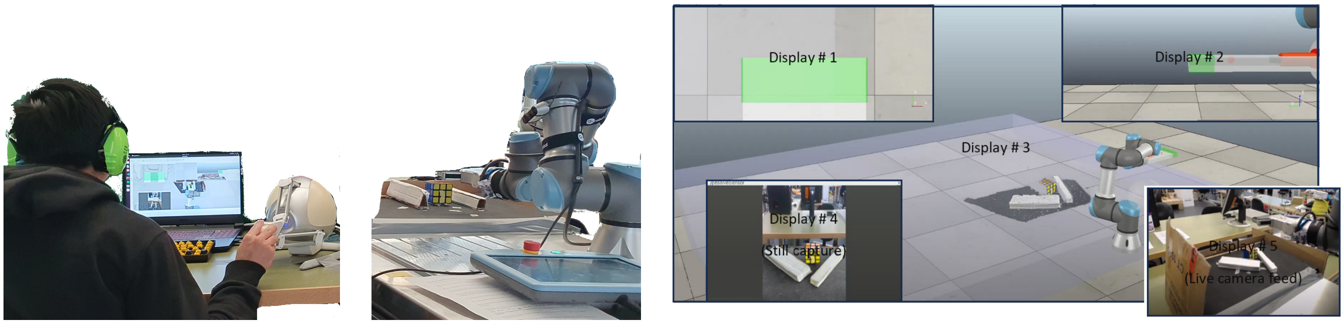


(a) (b) (c)

Figure 1: (a) An operator using the Haptic Device to control the UR3 manipulator in (b); (c) The display configuration provided to each participant.

positional awareness of devices they are controlling [12].

Haptic device integration into robotics is still in its infancy, with technological advances in the area being limited [13]. This is due to the complex requirements of producing kinaesthetic feedback that accurately reflects the robot's environment [12]. However, in recent times, there has been a noticeable increase in haptic feedback technology. This has the potential to enhance the meticulous control of robots when using these devices. This can be contrasted to unintuitive traditional forms of control where the issues lie in the lack of precision [14]. For example, haptic feedback in robotics provides a solution for a more natural method of rock scaling by allowing for precise manoeuvres within fragile work environments [15]. Implementing haptic feedback based controls schemes into these operations reduces task-specific risks while matching the sensitivity and manoeuvrability of working without machinery at all [16][17]. It would also enable more finely tuned movements through an additional sensing modality [18]. Furthermore, haptic devices can elevate the operator's situational awareness within the space of operation as if they were the robots themselves [7][17].VR-controlled robotic systems used in rock scaling currently exist and have the capability to support additional control schemes [7].

Thus, the need to integrate a haptic feedback device on top of the existing VR system becomes feasible and has great potential. Successful integration of the two systems would offer tactile perception on top of the visual and immersive benefits of VR in robotic control.

1.3 Paper Overview

Using a human-in-the-loop control strategy, the robotic platform can navigate in various unknown environments. The VR environment provides an interface that operators use to visualise RGB-D sensor data of the environment and enables control decisions made by the operator to be executed by the robot. The haptic feedback allows for a more informed method of manipulator control, allowing the user to feel the environment felt by the manipulator through haptic feedback. The paper is organised as follows: Section 2 presents the methodology used to create the haptic feedback system. Section 3 describes the experimental setup used to collect data. Section 4 examines the system's capabilities through laboratory and field testing results. Section 5 identifies and discusses the limitations and findings of the conducted user study. Finally, Section 6 presents the conclusions and future areas of research.

2 METHODOLOGY

2.1 Real Manipulator Platform

The robotic platform consisted of a six-degree-of-freedom UR3e industrial robotic manipulator manufactured by Universal Robots GmbH as shown in Figure 1(b). An Intel RealSense RGB-D mounted on the first link of the robotic system is used to capture a still image (Figure 1(c) Display 4) as well as capturing a still depth image of the real-world environment (Figure 1(c) - Display 1, 2 & 3). These still images are captured before the user operates the manipulator and are used for creating a haptically interactive object. Additionally, a two-finger RG2 gripper (OnRobot) on the end effector was used to perform grasping tasks within the experiment. The control framework, presented in Figure 2, allows various components to interface with the real robot platform and utilises the Robot Operating System (ROS) middleware. This programming interface is the foundation of the system.

2.2 System Integration and Communication

The Robot Operating System (ROS) is the foundation behind all hardware and software components communication. The ROS middleware also allows recording all data published to topics for later playback and data analysis. All task and experiment-related data, including

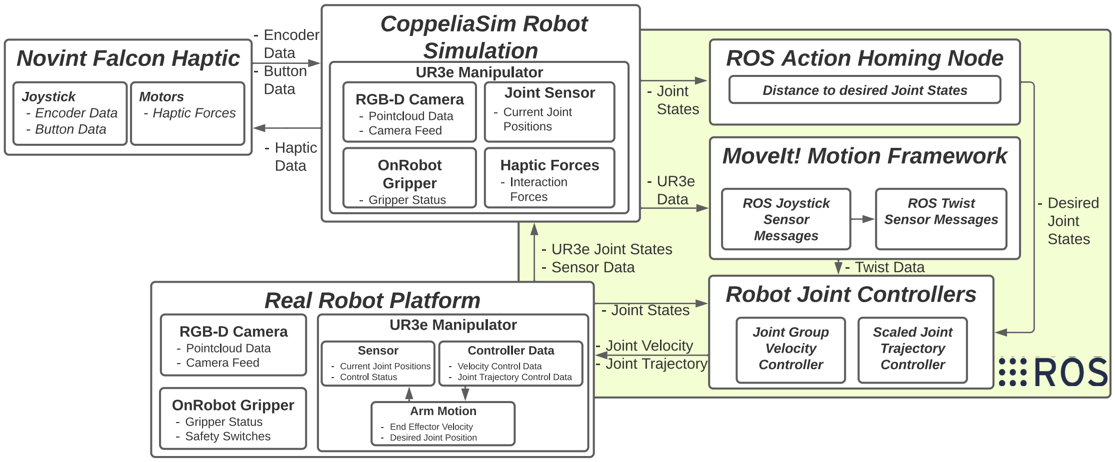


Figure 2: System overview

user joystick inputs, captured point cloud data, camera images, robot joint states and velocities or trajectories, are communicated through the ROS.

2.3 Robot Simulation in CoppeliaSim

The system's current state was visualised through the simulation environment CoppeliaSim. The simulation space accurately represents the robot's real-time joint and gripper states, and the RGB-D camera's still depth image is presented as a point cloud. The data is processed through non-threaded Lua scripts embedded within CoppeliaSim. These scripts are also responsible for communication through ROS topics and services to advertise information like the state of the Novint Falcon haptic device or for manipulator and gripper control.

In addition, haptic rendering was handled through CoppeliaSim by utilising CHAI3D, an open-source C++ library for computer haptics, as an extension module. Another extension module of CoppeliaSim, known as SurfRec, was employed to reconstruct point cloud data to produce a haptically interactive surface mesh. This mesh is constructed from the points obtained by the RGB-D sensor onboard the robotic platform. Utilising CoppeliaSim in this manner creates a cohesive system that facilitates bridging the CHAI3D haptic rendering framework to ROS for 2D visualisation. Using CoppeliaSim as the foundation for simulation allows for the future implementation of VR for visualisation.

2.4 Novint Falcon Haptic Controller

The Novint Falcon haptic controller was utilised to manipulate a cursor within CoppeliaSim. This cursor controlled the robot manipulator and received interaction forces from meshes within the haptic environment. The haptic controller provides force feedback to the operator when the virtual cursor comes into contact with objects rendered haptically. The physical limitations of the haptic controller's workspace are also used to provide the user with a reference to the manipulator's maximum working radius. Another feature integrated into the controller's function was maintaining an elastic-like attraction to the manipulator's end effector. This elastic-like attraction is referred to as a point constraint force and provides kinaesthetic awareness of the robotic manipulator relative to the controller. The device's buttons allow pitch and yaw control of the robotic manipulator as desired.

2.5 MoveIt Motion Framework

The MoveIt Motion Framework was used to allow the participant to control the UR3e manipulator in Cartesian space. The MoveIt Realtime Arm Servoing ROS package allows for end effector velocity control. Although the package is capable of collision avoidance, it was not included during experimentation as this would influence haptic, or lack of, feedback-derived collisions. This movement framework addresses the issue of kinematic singularities with velocity control of a robotic manipulator by slowing down the manipulator exponentially using the Damped Least-Squares approach [19].

2.6 ROS Action Homing Node

The ROS action homing node removed larger gross movements and allowed participants to focus solely on the fine movements during the manipulation task. This homing sequence was triggered from the ‘h’ key on the keyboard. While at the ’homed’ position, the system captures another depth image and updates the haptically interactive point cloud. The point cloud is processed into a surface mesh interactable by the user for the next repetition of the experiment.

2.7 Live Webcam Camera Feed

The real-time camera feed is provided to the user with an isometric perspective of the workspace through a webcam external to the robotic platform. This webcam solely provides live footage through the external Display 5 (Figure 1(c) on configurations 2 and 4 (Table 1). This system analyses the participant's potential reliance on their visual sensing modalities while interfacing with the environment through the robotic platform.

3 EXPERIMENT SETUP

This user study was designed to investigate the effect of haptic feedback on participant performance and subjective cognitive workload during control tasks involving teleoperated robotic manipulators. On top of this, the interactive effect on task performance resulting from additional visual and haptic feedback was also analysed. Similarly, this interactive effect between both sensing modalities on a participant's given cognitive workload was also explored. The results of this interaction were measured via a real-time webcam feed of the workspace when allowed by the specified task configuration (Table 1).

This effect on task performance was examined by conducting a user study, where participants were asked to complete simple robotic control tasks. This involved manipulating and completing an objective within two differing preconfigured workspaces (Figure 3). The first is narrow (Figure 3(a)), and the second is obstructed (Figure 3(b))to emulate the objective of removing loose flakes of rock. These two layouts are accurate to scenarios present in rock scaling applications.

Participants were asked to control the robot using the haptic controller to grasp the desired object with the installed two-finger gripper. The robot utilised end effector velocities provided by the haptic cursor in the simulation space as the method of motion. This cursor moved in response to the movement of the haptic device as controlled by the user.

3.1 Participants

A total of 10 volunteers (9 male, 1 female) with ages ranging from 19 to 25 (M = 22.2, SD = 1.69) participated in the experiment. Participants provided informed consent and completed a questionnaire to self-assess their experience with robotic control on a linear scale of 1-10, where 1 represented "No experience", and 10 indicated "Significant levels of experience". On average, participants reported relatively limited experience working and controlling robots (M = 3.56, SD = 2.30). Among the responses, 2 participants recorded a 1 for experience working with robots, with the highest recorded value being 7 out of 10.

3.2 Interfaces

In all configurations, participants controlled the robotic manipulator with the Novint Falcon haptic controller with only the end effector point constraint force enabled. This point constraint force can be described as an elastic force that pulls the joystick to the virtual location of the end effector within the haptic device's physical workspace. The participants can pitch and yaw the end effector relative to the robot's base transform using the buttons available on the haptic device. Keyboard shortcuts were also provided to roll the gripper (left and right arrow keys), start the experiment (space bar), and conclude the experiment repetition ('h').

Configuration 1 (no haptics, no camera feed): In this configuration, the environmental haptic rendering of the point cloud is disabled, and the external camera feed is also disabled. To navigate through the environment, participants were solely provided with Displays 1 to 4 (Figure 1(c)).

Configuration 2 (no haptics, camera feed): In this configuration, the environmental haptic rendering of the point cloud is disabled, and the external camera feed is enabled. To navigate through the environment, participants were provided with Displays 1 to 4 (Figure 1(c), similar to the last configuration, with one extra monitor (Display 5) portraying a live camera feed of the actual workspace and manipulator.

Configuration 3 (haptics, no camera feed): In this configuration, the environmental haptic rendering of the point cloud is enabled. However, the external camera feed portraying the physical workspace is disabled. To navigate through the environment, participants were provided Displays 1 to 4 (Figure 1(c), presenting the CoppeliaSim environment with the added haptic sensing modality and the purely simulated form of visual feedback via the point cloud surface mesh.

Configuration 4 (haptics, camera feed): In this configuration, the environmental haptic rendering of the point cloud is enabled, and the external camera feed portraying the physical workspace is enabled. To navigate the environment, participants were provided with all five views (Figure 1(c) portraying the CoppeliaSim environment with the extra added haptic sensing modality and the simulated and real live camera feed of the working environment.

4 Experiment Design and Procedure

With the simulated robot, participants controlled the robot through 8 different repetitions and were told to complete the grasping task "as quickly as possible with little disturbance to the environment".

These experiment repetitions are broken up into four configurations of 2 repetitions. The participant is given a random configuration to minimise any learning bias associated with system use. After every repetition, the environment will change. This change of the environment can be characterised by the repositioning of the obstacles surrounding the desired gasping object (Rubik's cube), in turn exposing the participant to an overall of 2 predetermined scenes. The first is Environment 1 (Figure 3(a)) and Environment 2 (Figure 3(b)).

After completing both environments in one configuration, the available feedback systems (haptic feedback and camera feed stream) will change randomly. The participant will be partitioned off from the real robot throughout the experimental process and given earplugs to simulate remotely controlling the robotic system. Additionally, earmuffs are used on top of the earplugs, inhibiting any auditory advantage that exposure to the actual hardware can provide during operation.

Before commencing the experiment, each participant is given 4 minutes to familiarise themselves with the control system of the manipulator without the predetermined environment. The participant will then feel a virtual object unrelated to the experiment to acclimate them to the sensation of a virtual haptic object.

After the timer has ended (4 minutes), the preparation phase will end, and the environment will be set up out of the participant's sight. Participants will then be informed that they can commence experimental operations when completed. The user will then begin by using the space bar keyboard shortcut to start the timer and, when perceived to be lined up with the object, will press the 'h' keyboard shortcut to end their attempt.

Upon completing each task repetition, the participant completes a form to measure subjective cognitive workload and perceived reliance on haptic feedback. This form will be further explained in the next section.

In the case of an emergency stop, as determined by the fail-safe features within the UR3e manipulator, the configuration would be reconfigured, and the participant would start again using the following environment or an altered experiment configuration.

4.1 Experimental Measurements

Objective Task Completion Time:

Task completion time refers to the duration from when the user initiates the task by pressing the designated start button (space bar) to when the end repetition button ('h') is pressed, signifying task completion.

Objective Task Accuracy:

Task accuracy was defined as the difference (error) in position from the gripper's centre to the selected object's centre. The position error was determined by calculating the Euclidean distance between the translational component of the two objects' transforms.

Objective Task Collision Count:

The task collision count is defined as any contact the robotic manipulator makes with its working environment. This consists of the workspace floor or obstacles specific to the experiment.

Subjective Cognitive Workload NASA-TLX:

After completing each repetition, participants were asked to complete a NASA-TLX form. This form is a subjective measure of the task's cognitive workload primarily used for human-robot interaction research. This cognitive workload is organised into six items: mental, physical, temporal, performance demand, performance, effort, and frustration scores. These are all rated on a scale of 1-10, with 1 being low demand and 10 being high demand, apart from performance, where 1 indicates good and 10 represents poor performance.

Subjective User Experience:

After each repetition, participants were asked to record the display format they used most. At the end of all the experiments, the participants were also asked "On a scale of 1-10, how helpful are the specific haptic forces during the completion of the tasks?" with 10 being helpful and 1 being not very helpful.

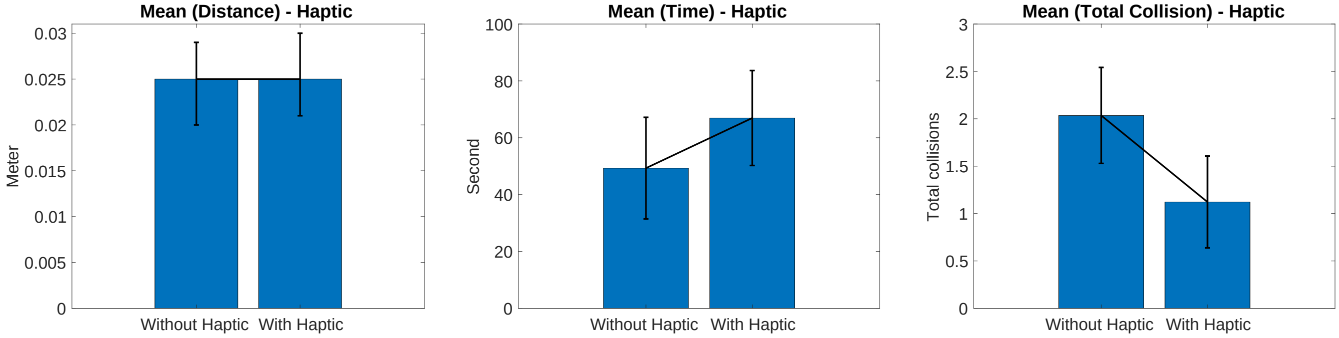
4.2 Hypotheses

From the experiments, participants were expected to achieve lower task completion times, higher accuracy, lower collision counts and lower cognitive workload while using the Novint Falcon haptic device with environmental haptics. It is also expected these results are amplified with the additional live camera feed. From this, three hypotheses were deduced:

- H1: When completing the tasks, the user will quantitatively achieve better results using the haptic device with environmental force feedback than no environmental force feedback. Better results are defined as (a) lower task completion time, (b) higher accuracy in position, and (c) lower collision count.
- H2: The user will subjectively achieve a lower cognitive workload using the haptic device with environmental force feedback compared to no environmental force feedback. This can be measured by (a) lower cognitive workload NASA-TLX score.
- H3: The user will quantitatively achieve better results and achieve lower cognitive workload scores using the haptic device with environmental force feedback and external display compared to their counterparts. Better results are defined as (a) lower task completion time, (b) higher accuracy in position, (c)

(a) (b)

Figure 3: (a) Environment Layout 1; (b) Environment Layout 2.



(a) (b) (c)

Figure 4: Average results with and without haptic feedback: (a) distance; (b) time; (c) total collision count.

lower collision count and (d) lower cognitive workload NASA-TLX score.

5 RESULTS

5.1 Analysis of Haptic Feedback Effects on Task Metrics and Cognitive Workload

Task Completion Time:

An ANOVA test analysed the measure task completion time due to or lack of haptic feedback, irrespective of other variables. Between the presence and absence of environmental haptic feedback, there was no significant statistical difference in task completion time (measured in seconds), F = 2.064, p = 0.155 between environment haptics (M = 66.94, SD = 55.03) and no environment haptic feedback (M = 49.33, SD = 50.11). This is shown in Figure 4(b). This data rejects hypothesis (H1a) demonstrating environmental haptic feedback does not positively affect task completion time. In actuality, haptic feedback increased task completion time by 35.70%

Task Accuracy:

In this user study, accuracy was defined by the distance of the end effector to the central position of the object. Between the presence and absence environmental haptic feedback, there was no significant statistical difference of position accuracy (distance in metres), F = 0.008, p = 0.927 between the environmental haptics configurations (M = 0.025, SD = 0.013) and no environment haptics (M = 0.025, SD = 0.014) configurations.This result was concluded by an ANOVA test and is displayed in Figure 4(a). This data rejects the hypothesis (H1b) by demonstrating that environmental haptic feedback does not play a significant role in producing better accuracy than the null hypothesis. In fact, there was a negligible 1.38% decrease in accuracy when adding haptics.

Task Collision Count:

An ANOVA test examined the effect that haptics had on the number of collisions with the environment during manipulation tasks. The test concluded that, F = 5.080 and p = 0.027, demonstrating that the presence of environmental haptic feedback (M = 0.95, SD = 1.176) provided a statistically significant difference in the collision quantity when compared to its absence (M = 1.7, SD = 1.742). This is shown in Figure 4(c). This data supports the hypothesis (H1c), demonstrating a lowered collision count compared to the null hypothesis. Specifically, there was a significant 44.12% decrease in collisions when haptic feedback was enabled.

Subjective Cognitive Workload:
Participants reported a similar cognitive workload as reflected through the NASA-TLX scores based on their experiences with haptic feedback (M = 3.091, SD = 1.751) and without haptic feedback (M = 2.917, SD = 1.730). The difference between these two is not statistically significant, with t(39)= 1.1665 and p = 0.654. This data rejects the hypothesis (H2a), which states that the introduction of purely haptic feedback-controlled teleoperated manipulators will increase the cognitive workload experienced by participants compared to not having haptic feedback. The difference between the two configurations resulted in a difference of 5%, with haptics proving to be slightly more taxing on the user's cognitive workload when utilised without the live camera stream. This slight difference proves no significance when comparing the contrasting configurations.

5.2 Evaluation of Haptic Feedback and Live Camera Stream Interaction: Task Metrics and Cognitive Workload

Task Completion Time:
An ANOVA test analysed the effect of environmental haptics with a live camera stream on the task completion time, as shown in Figure 5(c). The test concluded that with F = 0.396 and a corresponding p = 0.531, the combined effect of haptics and a live camera stream (M = 63.79, SD = 67.93) did not exhibit statistical significance when compared to their absence (M = 56.88, SD = 47.31) in terms of completion time. This result rejects the hypothesis (H3a).

Task Accuracy:
An ANOVA test analysed the effect of environmental haptics with a live camera stream on task accuracy. The test concluded that with F = 0.065 and p = 0.800, the combined effect of haptics and a live camera stream (M = 0.02697, SD = 0.01370) did not show statistical significance when compared to the absence of both environmental haptic feedback and a live camera stream (M = 0.02446, SD = 0.01295) regarding task accuracy. This result rejects the hypothesis (H3b).

Task Collision Count:
An ANOVA test analysed the effect of environmental haptics with a live camera stream on task collisions. The test concluded that with F = 0.361 and p = 0.550, the combined effect of haptics and a live camera stream (M = 0.85, SD = 1.03999) did not exhibit statistical significance when compared to the absence of both environmental haptic feedback and a live camera stream (M = 1.48, SD = 1.631176) regarding task accuracy. This result rejects the hypothesis (H3c).

Subjective Cognitive Workload:
The participant's cognitive workload during task completion was reflected in their NASA-TLX scores. It was observed that configurations including the combination of haptic feedback and a live camera stream (M = 2.39, SD = 1.45) exhibited statistical significance, t(39)=1.721 and p = 0.045, when compared to other configurations (M = 3.16, SD = 1.81).This data supports the hypothesis (H3d), which indicates that introducing haptic feedback and a live camera feed can reduce the cognitive workloads experienced compared to the alternative. The difference between the two configurations resulted in a difference of 75%, with haptics proving to be less taxing on the user's cognitive workload.

6 DISCUSSION

A haptic feedback-based control system was developed and implemented to investigate the feasibility of this emerging technology during teleoperative control of robotic manipulators for human-robot interaction. Using a physical robotic manipulator and environment introduced real-world factors, such as collision severity and object deformation, both being difficult to replicate through simulations. However, this approach still provided an effective method of quantitatively measuring task completion time, task accuracy, number of collisions and subjective cognitive workload. The results highlight the advantages of haptic feedback over traditional forms of control as demonstrated by the statistically significant differences found primarily in the objective measurements of collisions. These results are presented in Figure 4, where total collisions were the only variable that yielded statistically significant results when measured independently (Figure 4(c)).

Inversely, there were apparent negative and negligible effects demonstrated when introducing haptic feedback for both task completion time and accuracy, respectively. This would most likely occur when participants attempted to get the manipulator within grasping reach of the object. With the cursor dictating the final location of the end effector, participants were required to push "through the object". The haptic cursor had the possibility of sliding off or repelling users from the surface of haptic objects, possibly resulting in increases in times for each iteration. In a similar manner, this effect should also affect task accuracy, which may explain the negligible decrease in task accuracy. However, as the difference with and without haptics in regards to task accuracy is not statistically significant, further experimentation is required for a conclusion.

Another point of interest was the apparent lack of reliance on haptics, which participants personally experienced. Participants primarily gave the helpfulness of environmental haptic feedback an average of 4.1 out of 10. This was particularly interesting as the frequency of collisions within the environment seemed to contradict participant's subjective helpfulness scores. This may be a reflection of the intuitive or natural feel of the system towards the operator. However, conclusions can only be drawn if further user studies are conducted. On the other hand, the supposed lack of helpfulness of the haptic feedback may reflect the higher levels of cognitive workload recorded. This perhaps points to haptic feedback being distracting during segments of the tasks.

It was also observed from the user study that emergency stops, as determined by inbuilt safety features preexisting on the UR3e robots' software, were only evident for configurations that did not provide environmental haptic feedback. Specifically, Configuration 1 recorded three emergency stops and Configuration 2 recorded two emergency stops (Table 1). This further demonstrates the possibility that reliance on haptics is greater than the participants seem to acknowledge.

Config	**Haptics**	**Camera**	**Environment**
1	N	N	1
1	N	N	2
2	N	Y	1
2	N	Y	2
3	Y	N	1
3	Y	N	2
4	Y	Y	1
4	Y	Y	2

Table 1: A table listing all configuration combinations

An ANOVA test analysed the combined effects of haptic feedback and configuration iteration with respect to the task completion time. The results demonstrated a significant difference in times measured between the varying configuration changes during each participant's experimental repetition (F = 6.061, p = 0.001). As observed in Figure 5(a), task completion times were substantially more significant during the initial iterations of the experiment, followed by a gradual decrease as the participants progressed through their repetitions. It can also be observed in Figure 5(a) that task completion times during the initial iterations between the haptic feedback (Haptics-1) and the lack of haptic feedback (Haptics-0) differ to a large degree. However, the degree to which the two configurations differ decreases as task iteration progresses to subsequent repetitions of the experiment.

Comparatively, the interactive effect between haptic feedback and configuration iteration against environmental collisions also yielded statistically significant differences (F = 3.176 with a corresponding p = 0.03). Figure 5(b) demonstrates a higher number of environmental collisions during the beginning iterations of the experiment repetitions of those without haptic feedback compared to haptic feedback.

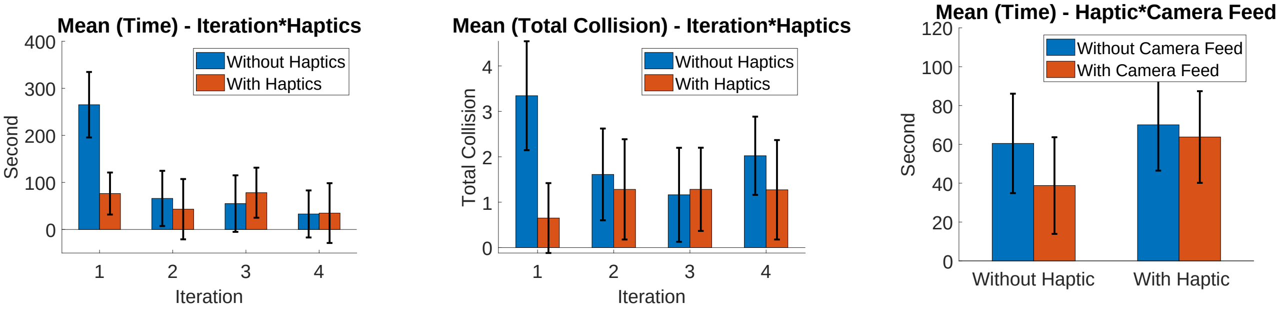
Both results may point towards the integration of haptic devices being an intuitive method of learning the control scheme of a robotic manipulator for newer users. However, with haptics demonstrating partially worse outcomes this requires further experimentation.

Participants were asked which display they favoured, with the external monitor (Display 5) recording the most views (Figure 6(b)). Additionally, it was recorded that 40% of participants noted that they preferred the external monitor containing the live camera stream as their primary source of visualisation (Figure 1(c)). Participants were only allowed to select the external monitor (Display 5) as the primary display during the configurations that it was provided (Table 1).

The additional camera stream was hypothesised to significantly aid the user's experience and objective task performance. However, this did not notably affect the user's performance. This result is contrary to hypothesis H3, where the inclusion of a external display is correlated with greater task performance. The lack of an effect on the users performance, despite having access to the most favourable display, could indicate that live camera feed only provides a subjective benefit to the participant. The lack of statistical significance may also be attributed to an absence of depth perception and the locked perspective view from the camera stream. This lack of benefit of the webcam stream may point to utilising existing VR systems as the primary source for visualising the workspace. Leveraging the benefits of VR, AR or MR provides depth sensing and complete immersive capabilities which are lacking in current static 2D camera feeds. However, further research must be conducted to conclude these claims.

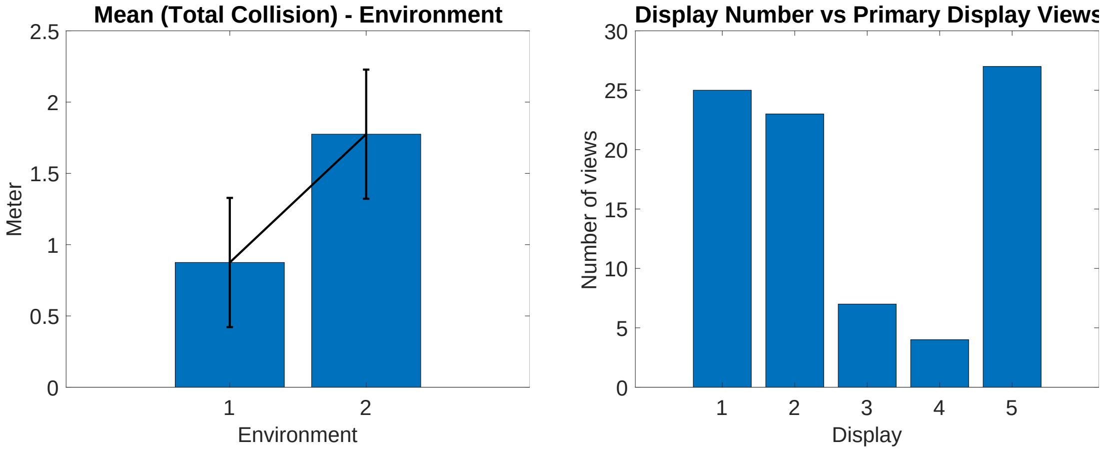
7 CONCLUSION

This paper discusses the potential integration of haptic technology into an existing virtual reality (VR) interface for remote operation of an industrial mobile manipulator. The goal is to enhance the operator's situational awareness. The independent haptic system showed a noteworthy decrease in collisions with the environment compared to control setups lacking haptic feedback. The results from the user study indicate that haptic feedback can reduce excessive environmental disturbance by



(a) (b) (c)

Figure 5: Consecutive repetitions with and without haptics: (a) task completion time; (b) environment collisions. (c) The average time for task completion using configurations with and without haptics and live camera stream



(a) (b)

Figure 6: (a) Environmental configuration with regard to collisions with the manipulator; (b) The subjectively selected primary display used during experimentation

avoiding unintentional collisions. However, the addition of haptic feedback also introduced higher task completion times and levels of cognitive workload from participants, possibly reducing immersion and contradicting the primary premise behind additional haptic feedback. It is due to these issues that further research must be conducted in this field.

In the future, there are potential aims to produce a haptic rendering system that processes and reconstructs point cloud data live to detect live changes in robots' environments. This future work would allow for increased immersion as the user would be capable of understanding changes that inflicting upon the environment.

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