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An experimental investigation of sensory feedback methods within teleoperation robotic systems

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Supervisors

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Affidavit

I declare that I have authored this thesis independently, that I have not used other than the declared sources/resources, and that I have explicitly indicated all material which has been quoted either literally or by content from the sources used.

Date	Signature

Abstract

This project serves as an experimental investigation into sensory feedback methods within teleoperation applications, focusing on vibration feedback and visual cues. A bilateral teleoperation system is developed on a semi humanoid industrial inspired robot using HTC Vive tracking technology as a control method. The design and implementation of a dual touch and proximity sensing system is documented along with the development of novel visual and vibration feedback systems. A study scenario with defined assessment criteria is outlined to evaluate the impact of the multiple feedback methods in relation to overall completion time, error rate, perceived workload (using NASA-TLX) and frustration. A 24 participant study is presented, with results demonstrating no significant findings in relation to the reduction of task completion time and error rate with the additional feedback systems. However, there are significant findings showing a consistent reduction of perceived workload across all tasks, due to the integration of vibration feedback.

Contents

1 Introduction

Teleoperation robotic systems are often defined as "operation of a system or machine at a distance" (Liu, 2019). Teleoperation allows for direct access to inaccessible and hazardous environments such as handling and disposing of toxic, explosive and nuclear material, and during space and underwater exploration. Teleoperation can also be used for applications within the medical sector including minimally invasive surgery.

Teleoperation robotic systems can be categorised into three main classifications, bilateral, shared and semi autonomous systems; depending on their level of autonomy. In bilateral systems, analog signals as well as real-time feedback are used to allow the operator to have direct control of the remote device. In shared and semi-autonomous teleoperation, the system anticipates an operators interactions with the environment and assists to allow for a better task performance. The operator monitors the system and provides high-level commands.

A teleoperation system that provides the operator with sensory feedback is referred to as a 'human-in-loop' system, where sensory feedback collected in the remote environment is provided and acted upon remotely. This is often referred to under the umbrella term of 'haptic' feedback although can be categorised into two main groups; cutaneous (force) and kinesthetic (pressure) feedback. This is covered in detail within Chapter 2.

Bilateral teleoperation systems have been developed since the mid 1940s where simple master slave systems were implemented to protect workers from radiation. It was soon realised that such systems required a feedback loop to improve deftness with electrical force reflecting position feedback being developed shortly after (Hokayem and Spong, 2006).

How sensory data is provided to the operator falls under three main subcategories; force, vibration and cue systems. Force feedback being the restriction of movement usually through a device featuring mechanical input. An example of this being 'Haptx', an exoskeleton system for both virtual reality and teleoperation applications (Goupil et al., 2019). Vibration feedback (or vibrotactile) is the use of vibration to replicate touch, interactions with environments and contact information to an operator. Cues systems are made up of two main subcategories; Auditory (AF) and Visual systems (VF), where direct haptic feedback is substituted for graphical or audio cues to portray information about the remote environment (J. T. Dennerlein, Millman, and Howe, 1997).

There is a considerable volume of research that looks into sensory feedback methods within teleoperation applications, with studies ranging from the impact of visual cue systems within space exploration (Nagai et al., 2002) to vibration feedback within underwater telerobotics (J. Dennerlein et al., 2000). Regardless of the diversity in applications and feedback systems, the majority of research uses time of completion as the metric for success. Whilst this is important, it should not be the sole parameter to measure the impact of a feedback method. For many teleoperation scenarios a key element is not to complete a task quickly but to complete it accurately. Furthermore if an operator is required to perform a task for a long period of time, it must not be too physically and mentally demanding. Some papers, such as (Whitney et al., 2020), assess the implemented systems in relation to system usability, focusing on the teleoperation system as a whole, while others focus on specifics relating to the application. (Okamura, 2004) investigating the 'average maximum tension on the suture' (a suture being a stitch or row of stitches holding together the edges of a wound or surgical incision) within RMIS (robot-assisted minimal invasive surgery).

The research studies detailed above are assessing a single metric of a specific teleoperation feedback method within a particular scenario. Due to lack of research material that details generalised teleoperation tasks, the present study aims to assess multiple tactile sensory feedback (visual cues and vibration feedback) methods in relation to effectiveness and the reflection this has on ease of use of the teleoperation system. These overall terms are analysed in relation to time of completion, error rate, perceived workload (using a widely used assessment tool) and frustration level. This allows for a wider understanding of the direct impact each feedback method has on simple teleoperation scenarios.

The hypothesis proposed are detailed below :

Hypothesis 1 *Participants will complete the task faster on the third (and final) attempt compared to the first attempt*

Hypothesis 2 *Both Visual Cues and Vibration Feedback will reduce the overall time of completion across all tasks (compared to No Feedback)*

Hypothesis 3 *Vibration Feedback will reduce the overall time of completion compared to Visual Cues*

Hypothesis 4 *Both Visual Cues and Vibration Feedback will reduce the error rate across all tasks (compared to No Feedback)*

Hypothesis 5 *Vibration Feedback will reduce the error rate compared to Visual Cues*

Hypothesis 6 *Visual Cues and Vibration Feedback will have a lower perceived workload irrespective of the task*

Hypothesis 7 *Vibration Feedback will lower the perceived workload compared to Visual Cues*

Hypothesis 8 *Visual Cues and Vibration Feedback will reduce the frustration level across all tasks*

Hypothesis 9 *Vibration Feedback will reduce the frustration level compared to Visual Cues*

Presented in this thesis is the development of a teleoperation system using Rethink Robotics Baxter robot and an HTC Vive system (shown in Fig. 1), the development of both visual and vibration feedback systems and a covering of related sensor technology. A study of 24 participants is outlined to assess the impact of the implemented visual cues and vibration feedback within a static teleoperation environment.

This thesis is divided into six chapters: Chapter 2 gives an overview of teleoperation and related history, artificial sensing within robotic applications, sensory feedback methods, tracking systems associated with teleoperation and data analysis methods used in current research. Chapter 3 outlines the development and experimental work carried out in the project. Chapter 4 covers the implementation of a study scenario along with proposed data collection methods. Chapter 5 sets out the research findings and data analysis and Chapter 6 covers future work alongside a conclusions of the study in Chapter 7.

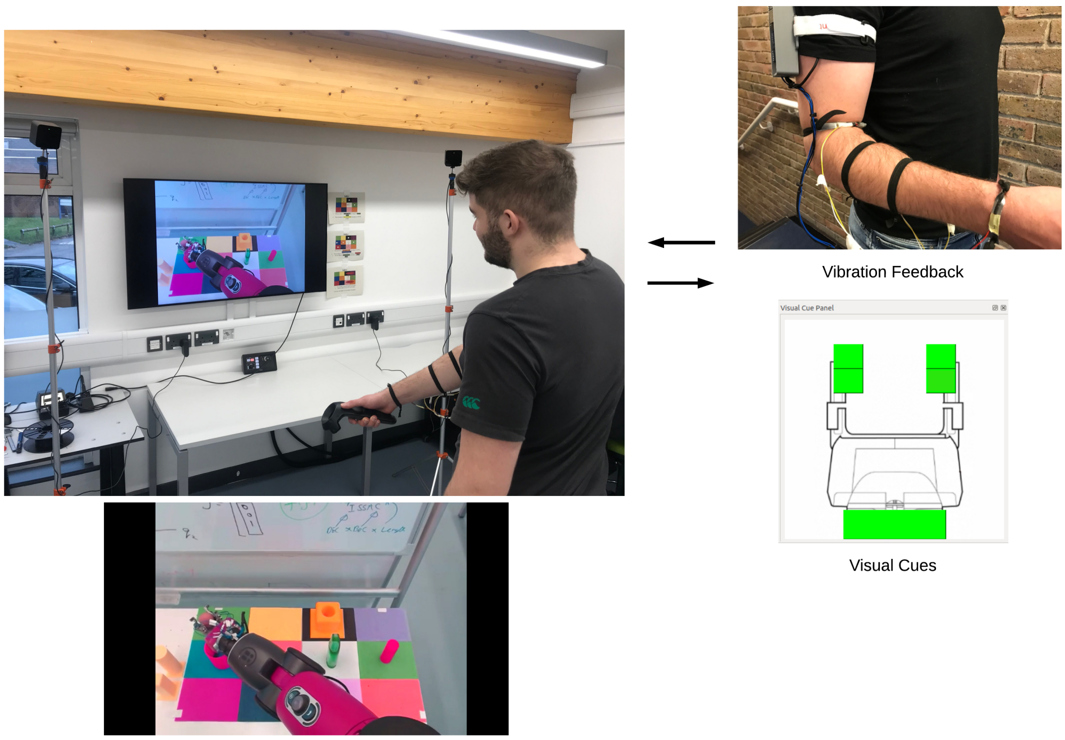


Fig. 1: The final implemented system being used during a teleoperation task.

2 Literature Review

2.1 Overview of Teleoperation

Teleoperation is an area of robotics that indicates the operation of a system at a distance. This type of robotic system is referred to by many different terms including telerobotics, telemanipulation, telepresence or teleaction. In this instance the robotic system will be referred to as 'teleoperation' throughout the paper. Teleoperation has a number of uses, for example it allows for interaction with environments, along with direct access to inaccessible, hazardous environments including handling and disposal of nuclear, toxic and explosive material, space and underwater exploration, minimally invasive surgery, entertainment and training applications (J. Dennerlein et al., 2000). Along with this teleoperation systems allow for human motion and forces to be scaled to fit specific task requirements.

These systems can be categorised into three main classifications, bilateral, shared and semi autonomous systems, depending on their level of autonomy. In bilateral systems the interaction with the remote environment is solely driven by the operator and is exclusively based on analog signals, the operator being strongly coupled with the environment (Hirche and Buss, 2012). In shared and semi-autonomous teleoperation, the system anticipates an operators interactions with the environment and assists them with the task, resulting in a better task performance. An example of this type of assistance being obstacle avoidance during a manipulation task.

Bilateral teleoperation has been developed since the mid 1940s with the first master-slave teleoperation system being built by Raymond Goertz's group at the Argonne National Laboratory. The goal of this initial system was to protect workers from radiation whilst enabling precise manipulation of materials. It became clear that it was important to have haptic sensing for manipulating delicate objects. To combat this requirement, Goertz implemented a force feedback system to improve the deftness of the control system, implementing an electrical force reflecting position servomechanism developed in 1954.

An increased interest in the 1960s led to several developments within the field, these included gaining an understanding of the effects of delay on teleoperation (Ferrel, 1965; Sheridan Ferrel, 1963) (Hokayem and Spong, 2006). To date there has been an abundance of research into teleoperation, specifically into the impact of haptic sensing within teleloperation applications.

It is key to distinguish the core terminology of 'haptics' regardless of the application. As an umbrella term, haptics generally describes touch feedback Okamura, 2009 although for a truly haptic system (whether that be in teleoperationn or virtual reality) a system must have substantial information from both cutaneous (force) and kinesthetic (pressure) feedback.

On a primitive biological level, cutaneous sensing receives sensory inputs from receptors embedded in the skin whereas kinesthetic sensing receives sensory inputs from receptors within the muscles, joints and tendons (Dahiya and Valle, 2013). Shown by (Kappassov, Corrales, and Perdereau, 2015), kinesthetic and cutaneous sensing are key to humans maintaining a grip during manipulation tasks. Children with deficient tactile sensing and people with anesthetized fingertips experience difficulties completing tasks with their hands. This difficulty extends into teleoperation robotic applications with the feedback loop being imperative to haptic perception, manipulation and maintaining a grip.

In robotics haptics is broadly defined as real and simulated touch interactions between robots and real/simulated environments. This definition can be broken down further into how these stimuli are perceived in robotic applications; cutaneous or tactile perception, kinesthetic perception and haptic perception. Tactile sensing within robotic systems is the detection and measurement of forces in a predetermined area. Depending at which point a sensor is located can affect how it is categorised, either intrinsic or extrinsic. Intrinsic sensors are placed within a mechanical structure (a motor or joint) and derive forces such as torque, whereas extrinsic sensors are mounted at the point of contact with a surface and deal with information from a specially defined area (Dahiya and Valle, 2013).

A teleoperation system that provides the operator with haptic feedback is an example of a "human in loop" control system (shown by Fig. 1). The operator is provided with sensory feedback to manipulate the environment they are in, this implies a "bilateral exchange of energy" between the human and the remote environment (Hirche and Buss, 2012).

To ensure a useful teleoperation system the user should be able to interact with the environment they are operating in, not simply command the equipment they are in control of. For such interaction a level of transparency is required, and for such transparency, sensing is imperative.

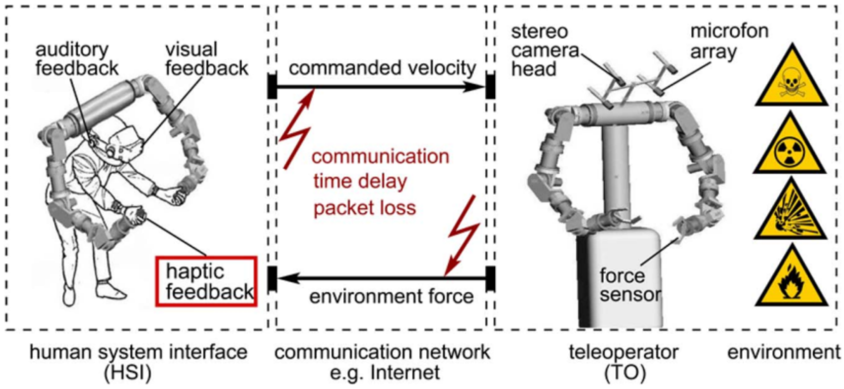


Fig. 1: Example of a 'Human in loop' system - (Hirche and Buss, 2012)

A human in loop based teleoperation system can be separated into four main elements; control methods, robotic hardware, sensing systems and feedback methods. This chapter provides a brief history of teleoperation robotics, related sensing technology, sensory feedback methods within teleoperation and investigates approaches to assessing teleoperation tasks within a study environment.

2.2 Sensing in Teleoperation Robotics

Research has been made into how the brain perceives, learns and uses sensory signals to aid in the manipulation and control of the surrounding environment. Whilst this provides insight, it is evident that the way biological systems process sensory information does not lead to the best engineering approach relating to robotic applications (Dahiya, Metta, et al., 2009).A large volume of literature provides a comprehensive coverage of the associated technologies in regards to sensing in both teleoperation and autonomous robotic systems.

A combination of both intrinsic and extrinsic sensing provides a much more detailed sensory system; extrinsic tactile sensors give a much higher level of precision and multi-modal information about the interaction with the environment, contact point estimation and slip detection (Wettels, Fishel, and Loeb, 2014). Some of the key tactile sensors used within robotic applications have been detailed below:

2.2.1 Piezoresistive Sensors

Piezoresistive sensors operate by changing the electrical resistivity of a semiconductor when mechanical pressure is applied to the surface. FSR (Force Sensing Resistor) are the most popular variant of this type of sensor. They are frequently used in robotics due to their low cost, accessibility, low noise and straightforward electronics. The main drawback of this type of sensor is that there are restricted contact locations due to the rigid material. Additionally, the linear response reduces the sensitivity in certain scenarios.

Fig. 2: An example of a Piezoresistive Sensor - FSR (Force Sensing Resistor)

2.2.2 Capacitive Sensors

Capacitive sensors allow high resolution pressure in a very small size. They are frequently used in robotics as they can provide force, vibration and temperature sensing along with being made into dense arrays. The capacitance is measured between two conductive plates, separated by elastic dielectric, as the force is applied the plates are moved closer in turn, changing the capacitance. Their robustness allows them to be able to withstand large gripping forces while still providing accurate results. This type of sensor is also used within commercial electronics including mobile phones. The main drawback of capacitive sensors is that they are prone to providing noisy intermittent readings (Maiolino et al., 2015).

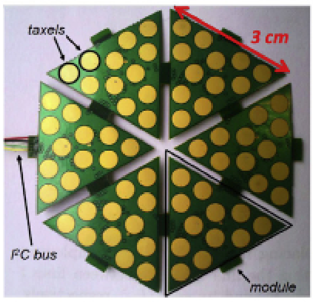


Fig. 3: An example of a Capacitive Sensor - (Maiolino et al., 2015)

2.2.3 Quantum Tunnel Effect Sensors

Quantum tunnel effect sensors (QTC) can change their properties from insulators to conductors under pressure. This makes them more technologically advanced than piezoresistive sensors, such as FSR's. These sensors can measure forces as low as 0.45mN in the x and y direction. Frequently used within robotics, they have featured in previous versions of the Shadow Dexterous Hand (ShadowHand, 2019). The main drawback of QTS sensors is that they are prone to wear, with the sensitivity reducing throughout this process. Additionally there are no commercially available products on the market for such sensors (Kappassov, Corrales, and Perdereau, 2015).

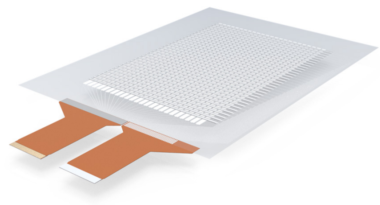


Fig. 4: An example of a QTC Matrix from Peratech - (Peratech, 2017)

2.2.4 Optical Sensors

Optical sensors function by using the change in light intensity to measure the pressure on a surface. Such sensors can measure forces as low as 5mN. Their main benefits include flexibility and sensitivity, along with fast communication. The main drawback of this sensor technology is the size and weight of the hardware itself, not being able to be applied in a large number of applications.

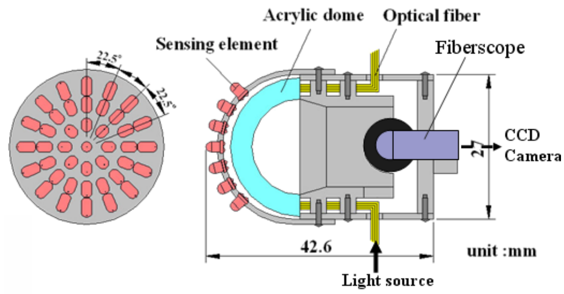


Fig. 5: Structure of optical three-axis tactile sensor - (Yussof et al., 2008)

Additionally, there is a large research focus on developing prototypes and new forms of tactile sensors. As is clear from the above, there are multiple types of flexible tactile sensors but none truly provide a sense of touch as the majority have limiting factors associated with them. (Kawasetsu et al., 2018) details a flexible tactile sensor that features a magnet, magnetic transducer and dual-layer elastomer and is capable of detecting an applied force and vertical deformation at a high sensitivity level. The system has no solid parts, sensing elements or wiring in the flexible covering. All electronic parts are separated, located away from the contact surface and in turn can be replaced without affecting the expensive electronics. This primitive concept would allow for a robot exterior frame to be covered in the flexible tactile sensor (Fig. 6).

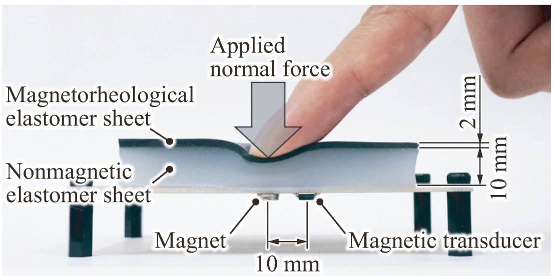


Fig. 6: Magnetic flexible tactile sensor, developed by (Kawasetsu et al., 2018)

Currently the most advanced sensory technology commercially available is the SynTouch BioTac (*SynTouch Sensor* n.d.), capable of sensing force, skin deformation, vibration and temperature identical to human touch capabilities. Changes in the impedance of electrodes on the surface material of the BioTac allows for accurate results. The BioTac being housed in a 'rigid core surrounded by an elastic liquid filled-skin to give a compliance remarkably similar to the human fingertip' (ShadowHand, 2019), this allows for deformation which is useful for the manipulation of small low weight objects.

(Arian et al., 2014) uses the BioTac system for tumour localization; centering on the high level of sensitivity to measure shear forces which arise as the sensor slides over artificial tissue and tumors. During the study the sensor was controlled manually, with no teleoperation implemented. Although it would be teleoperated within real world surgical applications.

Design criteria is highlighted as a key part of the development of a haptic teleoperation system. With the criteria not just focusing on the sensor technology itself, but also highlighting the importance of surface properties, wiring, sensor sensitivity, resolution and response criteria (Yousef, Boukallel, and Althoefer, 2011).

2.3 Feedback Methods Within Teleoperation

How sensory information from a remote environment is provided to the operator is a vital part of a teleoperation system. As raised by (Hasser, 1995) 'an ideal haptic feedback device possesses enough fidelity to "fool" the humans senses without wasting effort on fidelity that lies below the humans perceptual limits'. Feedback within teleoperation robotics can be split into three main subcategories Force, Vibration and Cue Systems.

2.3.1 Force Feedback

Force feedback can be found as far back as the 1940s when mechanically coupled master-slave systems were initially deployed in teleoperation systems (Sarakoglou et al., 2016). With the rise of Virtual Reality (VR) over the last 10 years there has been a large volume of interest within this area including the development of viable exoskeleton systems, an exoskeleton is an articulated structure which the user wears over their hand, transmitting forces to the fingers. An advanced version of such a system is Haptx. Regardless of the development of VR, the focus remains on entertainment, education and training sectors. The majority of force feedback systems make use of active force feedback, a device that restricts the movement of the user via a mechanical input, for example an electric motor. Force feedback has been very successful within RMIS (Remote-Assisted Minimally Invasive Surgery) with the systems typically measuring or estimating the forces applied to the patient by the surgical instrument, and providing resolved forces to the hand via a force feedback device (Sarakoglou et al., 2016).

2.3.2 Vibration Feeback

Vibration feedback (or vibrotactile) is the use of vibration to replicate touch and interactions with environments to an operator with minimal cost and complexity. Vibrations are used to signal key events during object detection and manipulation (J. T. Dennerlein, Millman, and Howe, 1997). Vibration feedback has been extensively developed for virtual reality applications and the entertainment sector, in turn reducing the cost of small vibration actuators and becoming increasingly accessible and more appealing for such remote applications. (De Barros, Lindeman, and Ward, 2011) develops a collision-proximity feedback interface using vibration feedback, or 'TactaBelt' as it is referred to. The system consists of eight pager motors (a pager motor being a small motor with an offset weight mounted on the drive shaft). The pager motors, or 'tactors', are arranged in a ring around the robot operators torso, with the intensity of vibration changing in relation to the distance and direction or surrounding objects in the remote environment. The study aimed to assess if the multiple feedback methods demonstrated an increase in navigational performance and situation awareness, these were measured by four factors ; a reduction in the number of collisions, a reduction in the time taken to perform the task, an increase in the number of objects found and an understanding of the environment. The study results showed that the group of both feedback methods (graphical and vibrotactile) drew better overall results and that vibrotactile feedback had no negative impact for all conditions. This drew the conclusion that 'the use of the interface in conjunction with other graphical CPF interfaces can improve operator situation awareness without detriment to cognitive load'. Additionally the results seemed to point to an increase in global situation awareness.

2.3.3 Cue Feedback Systems

There are alternative feedback methods to convey vital haptic information to the operator of telepresence systems. These are categorised as 'cues' and can be split into two main subcategories; Auditory (AF) and Visual systems (VF), with VF also being referred to as 'graphical'. (Okamura, 2004) focused on feedback methods within RMIS, substituting direct haptic feedback with visual and auditory cues. Here, an experiment was run that assessed the tension applied to sutures during the first throw of a surgical suture knot. Four different sets were studied, the first being no feedback, the second auditory (a single tone when the magnitude of the applied tension reached the 'ideal' tension) the third was a graphical display of the force levels, the final included both the AF and VF feedback (AVF). The paper presented some interesting results with regards to the analysis of the effectiveness of sensory substitution as a practical method of haptic feedback, these included a distinctive reduction of the coefficient of variance with the application of AF and VF along with precision being improved with the inclusion of VF and AVF (which provide continuous force information), but not AVF singularly. (Nagai et al., 2002) also developed an auditory system for teleoperation of space robotics, in which the majority of information is presented visually including distance, speed, orientation and trajectory information. An auditory system is developed to replace some of the visual information and in turn improve the decision-making of the operator. At the time of publishing, the paper was the first to propose this feedback concept specifically on space robotics.

2.4 Tracking Systems

An important part of a teleportation system is an accurate, yet natural control system. This is imperative within a bilateral system, with the control system being the foundations of the transparency between the operator and the remote enviroment.

In relation to bilateral teleoperation tasks, the main design goal, which ensures a close coupling between the operator and the remote environment, is that the slave manipulator should closely track the position of the master manipulator (operator) with constant stability throughout (Chopra et al., 2004). Although, positional drift due to environmental contact is a well known problem in such systems.

There are various methods of gaining positional data for teleoperation applications. The most primitive are keyboards, joysticks, dials and robot replicas. These are all commonly used but all require unnatural hand and arm motions to complete a task (Du et al., 2012). Depending on the scenario these control methods can negatively impact on task performance.

2.4.1 Vision Based Tracking

Many teleoperation systems use vision based techniques, with the focus being mostly marker based systems (although image processing using normal and stereo cameras has been used). Here, physical markers are placed on anatomical body parts to get position and orientation data within the 3D space. Such systems are limited in regards to finite movements and can lack when performing dexterous tasks. Occlusion is also an issue related to such vision tracking, where the marker cannot be seen by a camera due to an obstruction (Reddivari et al., 2014).

In the last 10 years with the release of devices such as the Xbox Kinect, there has been a push towards using markerless tracking within teleoperation applications. This has occured because the depth sensors are more accurate and can be used in real-time whilst providing positional data in cartesian space. The Kinect features an RGB camera and a dual infrared depth sensor. In papers such as

(Reddivari et al., 2014) the Kinect maps human joint position and velocities which enables a kinematic model to be formulated for the teleoperated robot.

2.4.2 Sensor Based Tracking

Both the tracking systems noted above are categorised as 'non invasive' as they require no physical sensors to be mounted on the tracked objects. There are tracking systems such as Cyberglove (Glove, 2016) that feature mounted sensors (traditionally flex sensors and more recently IMUs) to track the position and orientation. (Weber et al., 2016) developing a low cost sensor glove with the iCub robot for teleoperation applications.

2.4.3 Virtual Reality Technology

Although these 'invasive' tracking methods are very beneficial for dexterous tasks, specifically in hand teleoperated tasks, they tend to still rely on external tracking systems for the overall position and orientation data. With the renewed interest in Virtual Reality there has been an increased use of such controller technology within robotic applications, with papers such as [6] presenting a VR interface that allows an untrained user to control a robot arm to carry out fine-grained manipulation tasks. Using a VR engine the study provided the operator with a 3D model of the robot, an overlaid point cloud and a camera feed from the wrist of the robot. From this, the operator was able to directly control the robot arm end effector position with the HTC Vive controller.

HTC Vive is a virtual reality system developed by HTC and Valve. The Vive tracking relies on infrared lighting emitted by two fixed base stations (lighthouses). The headset (HMD) and controllers feature arrays of sensors (24 sensors on a controller and 30 on the HMD) which accurately track their location in relation to the Lighthouses. Additionally for accuracy and to aid motion tracking each device features a 6-axis IMU which integrates a 3-axis accelerometer and a 3-axis gyroscope, sensor fusion is also used to help stabilise the tracking. The HTC Vive uses room scale tracking technology to allow the user to move in 3D space, with the play area being up to 5m square (Brown, 2016) (*HTC Vive* 2020).

2.5 Assessment Methods of Teleoperation Systems

It is important to consider how a teleportation task can be assessed. There is a natural assumption that the key metric of measuring the effectiveness of this type of system is time, which in a lot of scenarios is true, although not the only metric that should be considered. More specific teleoperation such as RMIS and underwater telerobotics use other assessment criteria as the objective dependent variable.

(Okamura, 2004) focused on the average maximum tension on a suture (a suture being a stitch or row of stitches holding together the edges of a wound or surgical incision). This study tested between a hand tie, teleoperated tie and instrument tie. On the other hand, (Alex, n.d.) used both success rate and time across multiple tasks. These tasks included navigating a maze, ring stacking and comparing the weights in buckets with each participant being asked to lift each bucket individually and rank them in order of weight (a successful result being a correct answer of all weights). The study also implemented a usability test in order to investigate both participants proficiencies in using the system and their opinion of the robotic interface.

(Whitney et al., 2020) looked at the system usability by implementing a 'System Usability Scale (SUS), which asked users to rate 10 questions on a 7 point likert scale ranging from "strongly disagree" to "strongly agree". The questions covered different aspects of the system, such as complexity, consistency and cumbersomeness. Additionally, workload of the task was assessed by implementing the NASA-TLX, a widely used assessment tool that measures perceived workload of a particular task (Group et al., 1987). The workload was measured across six subscales ; mental demand, physical demand, temporal demand, effort, frustration and performance. The 'raw TLX' scores can be used for greater insight or a weighted calculation can be used to indicate an overall workload between 0-100, 0 being the lowest and 100 being the highest. All the above, in addition to time, serve as ways to assess the effectiveness of teleoperation systems.

A large volume of research material provides an overview of the technology related to sensing within teleoperation applications along with the various feedback methods associated. The majority applying a singular sensory feedback method into a particular teleoperation scenario with a specific assessment metric relating to that task. Furthermore time of completion being the main metric of assessment throughout.

3 Development

This study endeavours to narrow the gap in the research area by undertaking a series of real world teleoperation tasks with multiple sensory feedback methods, assessing the impact of such feedback methods on the teleoperation task in relation to effectiveness and ease of use. By using the assessment metrics of time of completion, error rate, perceived workload and frustration will allow for a greater understanding of the impact additional sensory feedback systems have in a teleoperation scenario.

In this chapter a bilateral teleoperation system is implemented on a semi humanoid industrial inspired robot using HTC Vive tracking technology, the development of a sensing system and multiple sensory feedback methods are documented.

3.1 Teleoperation Implementation

3.1.1 Rethink Robotics Baxter

At the core of the project an accurate teleoperation system was required, this being the initial focus and the first stage of development. An imperative part of this being the selection of appropriate robotic hardware. The Rethink Robotics Baxter was selected.

Baxter is a semi humanoid research robot that features a torso, 2 DOF head and two arms with 7 DOF joints, integrated camera, sonar sensors, torque sensors, collision avoidance and force sensing actuators (FSA) (Reddivari et al., 2014). Originally designed as an industrial robot, Baxter lends itself to the research field by being able to adapt to changes in the environment through the use of the integrated camera's and FSA's. Due to the length of the arms, 104cm from the shoulder joint to the end effector, Baxter is able to complete a range of tasks whilst maintaining accuracy and precision. Additionally the arms are compliant. This compliance is possible by using series elastic actuators, in which a motor and gearbox control a spring that drives the joints rather than directly controlling the joints. It's these springs that make each arm less rigid than typical robot arms (Johnson, 2018).

Baxter also features a software development kit (SDK) used for complete control via ROS (Robotic Operating System) as well as a full simulation suite and kinematics engine. Baxter can also be controlled in torque, velocity and position modes. For the teleoperation application Baxter robot is suited due to the built in safety features (collision avoidance) along with easy integration and development with the SDK and inverse kinematics solver. Furthermore the physical parameters of the robot are suited to this sort of application allowing an easy mapping between the human and the robot. Alternatives included the WidowX200 robot arm from Trossen, which does not feature safety features and was limited within the scale of the tasks due to it's size.

Fig. 1: Baxter Robot by Rethink Robotics

3.1.2 ROS

Robot Operating System (ROS) is a widely used open source middleware platform and flexible framework for writing software for robotic systems. ROS provides the services that are expected from an operating system (OS). For example, hardware abstraction, low-level device control, implementation of commonly-used functionality, message-passing between processes, and package management.

ROS provides a communication network (peer-to-peer network of processes) which can be separated over multiple machines. This allows complex and computationally heavy tasks of robotic systems to be separated. Each individual task is called a 'node.' The nodes communicate with each other using messages which pass via channels called topics (Tawil, 2017). Publisher and subscribers are used to send or receive data from another node via a master node.

ROS mainly uses C++ and python programming languages with the use of rospy and roscpp API's. Rospy and roscpp enable Python and C++ programmers to quickly interface with ROS topics, services and parameters. The design of rospy favors implementation speed (i.e. developer time) over runtime performance so that algorithms can be quickly prototyped and tested within ROS (*ROS Wiki* 2017). For time critical operations C++ is recommended within ROS.

ROS is an ideal software platform for the teleoperation application as it is flexible, widely used, fully compatible with Baxter and although it is not real-time is 'best-effort' in relation to timing.

Details relating to the final ROS implementation and system architecture can be found in section 3.5.2.

3.1.3 Tracking System

IMU Tracking

During research into tracking solutions used within teleoperation applications, multiple systems were reviewed. The initial concept was to develop an IMU (inertial measurement unit) based tracking system. Further research was made into hardware options for such an application, with the focus being a BNO080, a 9 axis IMU developed by Hillcrest Labs and Bosch Sensortec that incorporates an accelerometer, gyroscope and magnetometer. As the BNO080 features drift correction algorithms, it is able to produce accurate rotation vector headings, with a static rotation error of two degrees or less. Using a breakout version of the BNO080 platform, available from SparkFun electronics (SparkFun, 2019), multiple IMU's were integrated onto a microcontroller using I2C communication, allowing tracking of the upper and lower arm along with the wrist. Unity, a gaming engine for development of primarily virtual reality applications, was used to develop a basic humanoid morphology, with the IMU linked to the various objects in the chain, the end point position and orientation in global space was calculated.

Although this provided a primitive method of tracking an arm it became clear that the only way to get accurate positional data from an IMU based tracking system would be to use a kinematic model. This would have meant modelling each participant in the study, as individual people have unique physical characteristics. As creating a tracking system was not the sole focus of the study, it was decided that this was not within the scope of the project and alternative methods were considered.

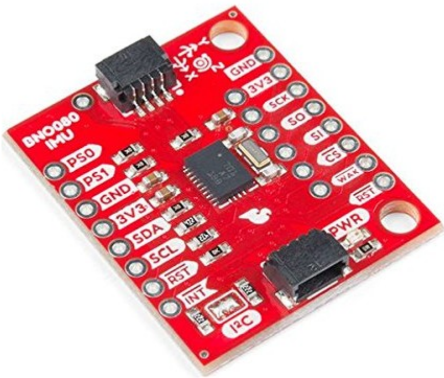


Fig. 2: BNO080 Breakout Board by Sparkfun Electronics

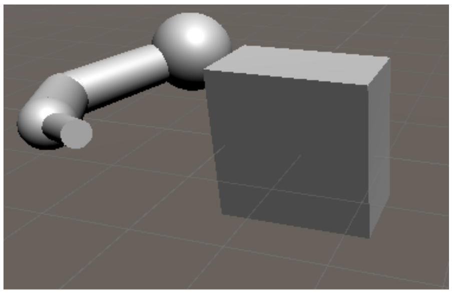


Fig. 3: Basic humanoid morphology IMU model

HTC Vive Based Tracking

During the research stages it was noted that multiple related studies had used virtual reality equipment as tracking solutions for teleoperation applications. A HTC Vive system was chosen as the platform to use for the tracking solution.

HTC Vive uses SteamVR, a virtual reality platform developed by Valve as an extension to Steam (a gaming distribution service). OpenVR is an API that allows for the development of virtual reality applications. It serves as an interface between the VR hardware and software. The openVR API allows access to functions such as position of the headset and controllers, button presses and advanced options such as haptic pulses and graphics rendering on a HMD (head mounted display). OpenVR is primarily based in C++ although python bindings, a wrapper library that bridge two programming languages, can be accessed unofficially allowing developers to program virtual reality applications in Python 3.5.

3.1.4 Teleoperation Integration

There are a few open source implementations of ROS based HTC Vive tracking solutions available online, (Pfeiffer, 2018) repository provides nodes to track the controllers and HMD that can be subscribed to through ROS. The implementation used the ROS tf (transform) package to maintain the relationship between the coordinate frames in a tree structure. The implementation also provided access to the device button presses using the sensor_msgs joy data type. Additional features included the ability to send controllers 'haptic pulses', in other words, a vibration command.

Furthermore, a previous research project had taken the above implementation and applied it the Rethink Robotics Baxter robot. The ROS HTC Vive tracking solution remained the same with the addition of an implementation that allowed the robots end effector position to be matched to the Vive controller position, using the built in inverse kinematics (IK) solver on Baxter. It is possible to use the IK solver to pass a position for the end effector in cartesian space. The implementation was developed by (Hew, 2018). Whilst this implementation was very effective, with large parts being incorporated into the project, there were changes required to enable the teleoperation system needed for the study.

Considerably, the largest change made to the Baxter system was to develop the way in which it tracked the controllers in the coordinate frame. The inherited system used the HMD as the base frame (the center position of the VR tracking) and calculated the distance difference from the HMD to the controllers. This was due to the previous application using a HMD to view a ZED stereo vision camera feed. This was not required within the study task and actually made the system increasingly difficult to control, relying on the operator keeping their head perfectly centered and straight throughout. This was overcome by changing the base frame to the global coordinate frame (the center position in relation to the fixed base stations) and creating a calibration function. The calibration function operated by utilizing the menu buttons on the Vive controllers to initialize a centre position, this position was then stored and deduced from any further positional data to calibrate the controller in a central position throughout, the calibrate function operating in the x,y,z axis in relation to position. There being no requirement to set a starting point for orientation of the controller. By adding this calibration calculation before the controller pose stamp was published, a pose stamp being a ROS data type that holds x,y,z position and quaternion orientation, it was possible to provide the robot with a calibration start position. Fig. 4 gives an overview of the basic principle behind the calibration function. Fig. 5 demonstrates the impact of the calibration on the system, the small axis being the original posestamp provided by the controller, the larger being the updated posetamp for the end effector position of the robot. Regardless of the position of the controller, the operator is able to calibrate the controller to a centre starting position. This alteration to the teleoperation system was vital. Because the study was dealing with multiple participants this alternation allowed for a comfortable operating position to be selected by individual participants.

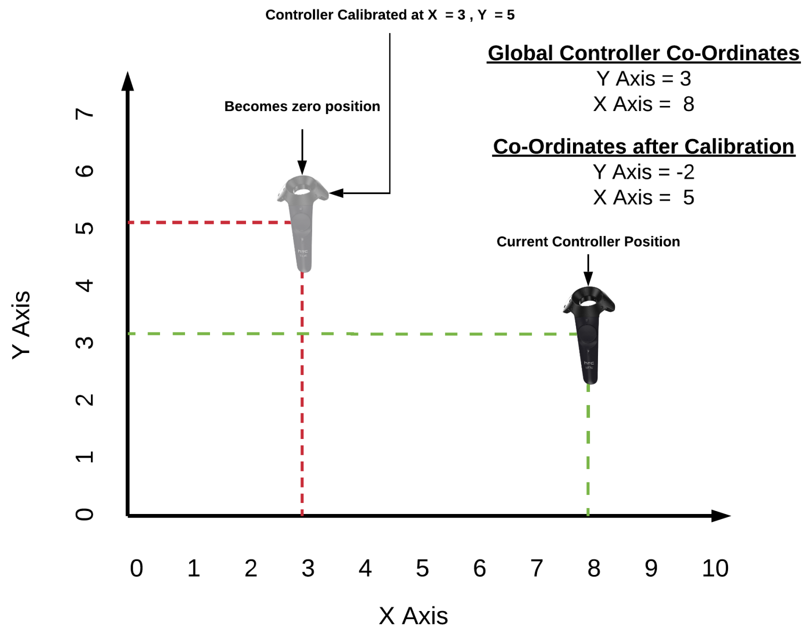


Fig. 4: Basic calibration logic, applied to X,Y,Z axis

The calibration function was only implemented in relation to the position of the controller and not the orientation. Although a calibration function could have been implemented in relation to the orientation, there was no requirement. The operator would be instructed to start from a centre position with the controller flat, due to this it was possible to use the global orientation with no modifications being made.

The previous implementation by (Hew, 2018) had also converted the original quaternion angles (provided by the controller posestamp) into euler angles for correcting orientation values. Although not documented it is assumed that this was to counteract orientation changes between the HMD and the controller. This use of euler angles caused bugs in the updated teleoperation

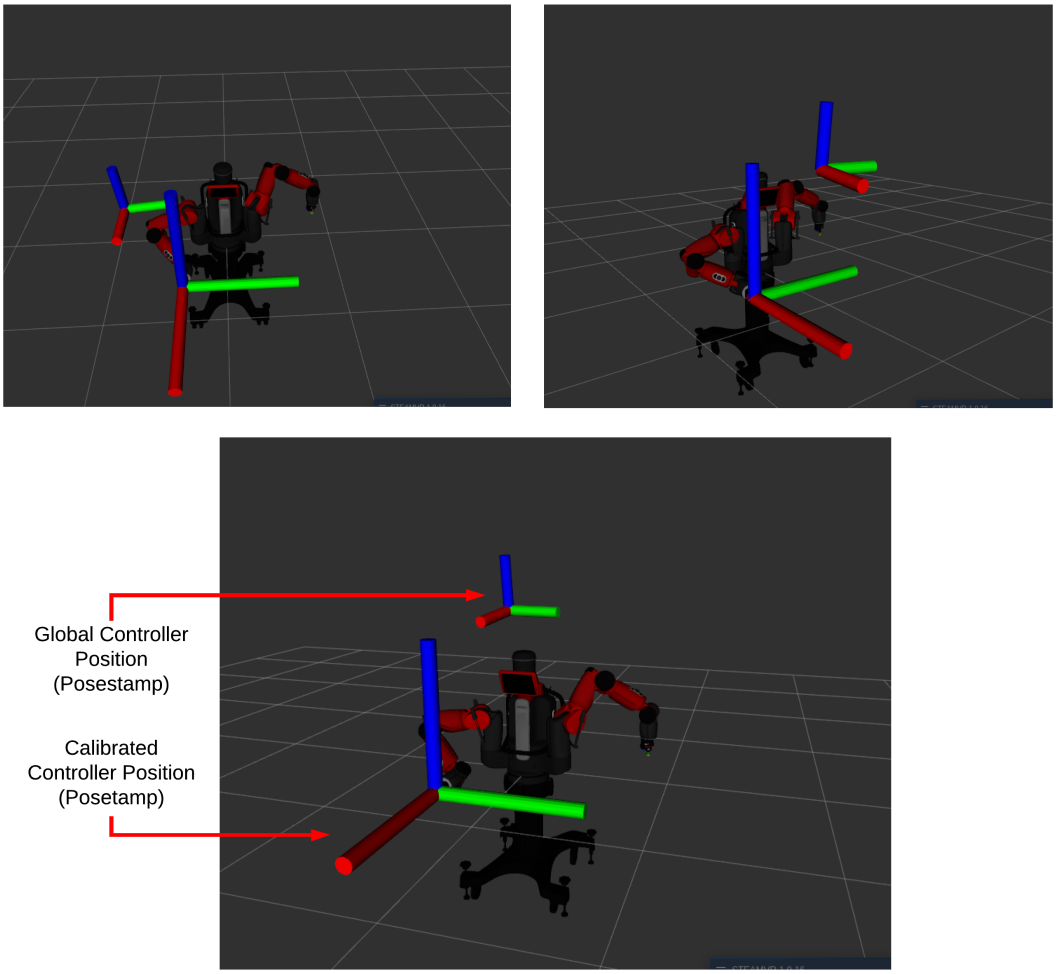


Fig. 5: The global position of the controller (small co-ordinate frame) and the output from the calibration function (large co-ordinate frame) are shown. This demonstrates that regardless of the starting position in the x,y and z axis the calibration function allows for the operator to select a starting position, with Baxter centre position remaining the same.

system, the solution being to pass the quaternion direct from the published controller transform to the inverse kinematics solver. Furthermore the original implementation provided the transforms in a left-hand coordinate frame which was incorrect and not suitable for this system, a large volume of VR applications use a left handed coordinate frame whereas robotic applications use a right handed frame. This was considered to be an error in the original Vive openVR implemenation.

Whilst testing the updated teleoperation system it was noted that there were extreme joint angle changes that did not appear to be due to joints approaching their maximum extension or limits. This led to an investigation into Baxters built in IK solver. An IK solver calculates the joint configurations in relation to a desired end-effector pose based on a specified rigid body tree model (D'Souza, Vijayakumar, and Schaal, 2001). Baxter features an IK solver with various parameters. After investigating the API documentation it was found the 'seed' parameter was causing the erratic behaviour. The basic principle behind seed's in the IK solver is where the joint angles base their solution from, by changing the parameter to look for possible joint solutions around the current joint angles the IK solver was much more stable without erratic changes in the arm position.

There were small additions to the core teleoperation implementation including the system being reduced to operate only on a single arm. Due to the teleropation task there was no requirement for the second arm, meaning we were able to remove the anti collision and increase the motor velocities, in turn making the teleoperation system more realistic to the operators position. Additionally, an emergency stop button was implemented on the Vive controller for the use of the operator to stop the task at any time.

3.1.5 Camera Feed

The key to an operator being able to see the environment they are teleropating in is an efficient video feed (also known as a camera feed). These camera feeds can be mounted in multiple locations on the robotic appertratus to allow for greater accuracy during object detection and manipulation. With the development of camera technology, stereo camera systems have been implemented into teleoperation applications to allow for a greater depth perception.

As the study focused on evaluating the tactile sensory feedback methods themselves the decision was made to implement a single camera system. The logic being that by not providing considerable depth perception within the remote environment it would force the participants to rely on feedback methods. In turn reflecting the impact of such feedback methods.

The Logitech C920 HD Pro webcam was chosen as the video device, as it was economical whilst streaming 1080 resolution at 30 fps. This camera was implemented with ROS usb_cam package that allows USB based camera devices to publish images as the sensor_msgs image data type, this package uses the image transport library to allow compressed image communication across a network.

At this stage it was possible to fully teleoperate the Baxter robot in another location with a camera feed provided to the operator.

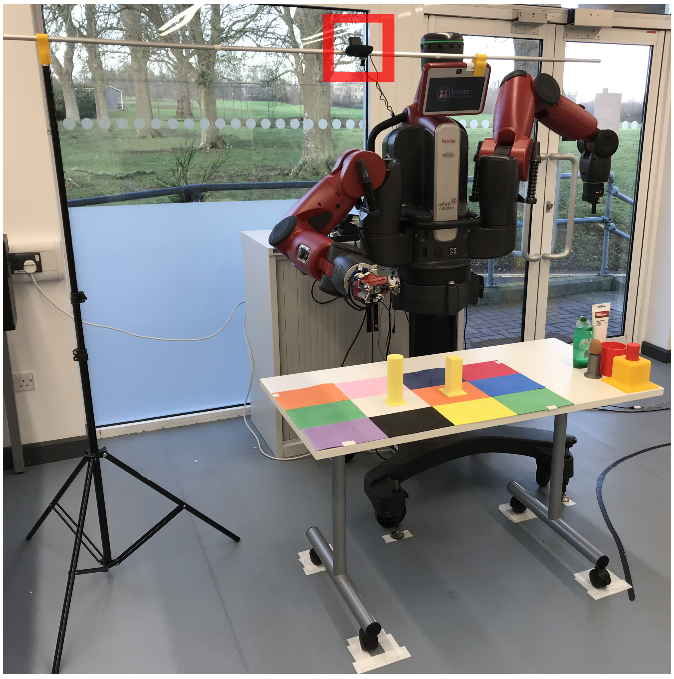


Fig. 6: Position of camera during teleoperation task, shown in the red box

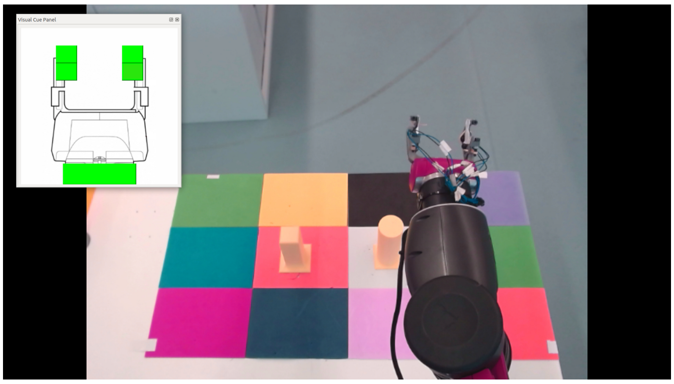


Fig. 7: Operators view of video feed

3.2 Sensor Selection and Implementation

Although previous research was carried out on sensing methods within teleoperation applications, a period of time was spent investigating multiple sensors within the parameters of the specific system. Other factors, including the scope of the project and economic constraints, were considered during this stage.

Piezoresistive sensors, more specifically FSR's (force sensing resistors) were considered the most appropriate choice for the application due to their sensitivity level, accessibility and simple implementation. A simple gripper concept to house the FSR's was developed and implemented on Baxter (Fig. 8), allowing for testing to be undertaken assessing the efficiency of the sensory information.

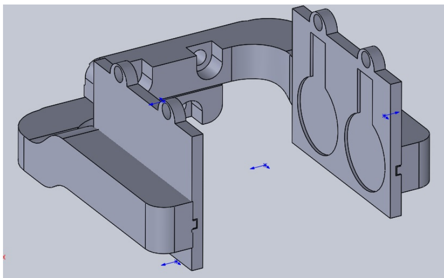


Fig. 8: Initial Gripper Concept

Following a short amount of time testing the system, it was noted that although FSR's are sensitive to change in pressure they would only react to firm pressure, in order to really gain useful information with regards to object interactions in a remote environment the 'onset' (or first contact) to such objects is imperative. 'Onset' refers to the small interactions that occur before grasping the object itself. The standard FSR sensor did not allow for this discrete sensory information.

A testing apparatus was developed to get an exact reading in relation to force applied to the FSR sensors and the readings outputted from the micro controller. Fig. 9, shows the bench test used that measured the exact pressure applied to the sensor. The sensors were analysed in multiple configurations; the raw sensor with no additional covering, the raw sensor with a rubber pad, the raw sensor with a foam pad and the preloaded FSR system (implemented later). The results from this can be seen in Fig. 10 where it can be observed that there is no change in sensor readings below an applied weight of roughly 25 grams, regardless of the additional rubber or foam pads. Both additional pads amplify the sensor sensitivity when forces are applied greater than the 25 gram threshold, although the rubber pad requires slightly more pressure before a reading is present.

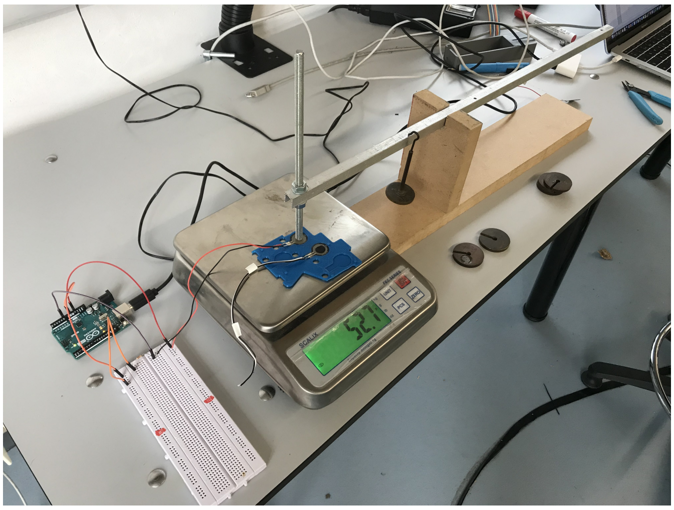


Fig. 9: Bench test apparatus

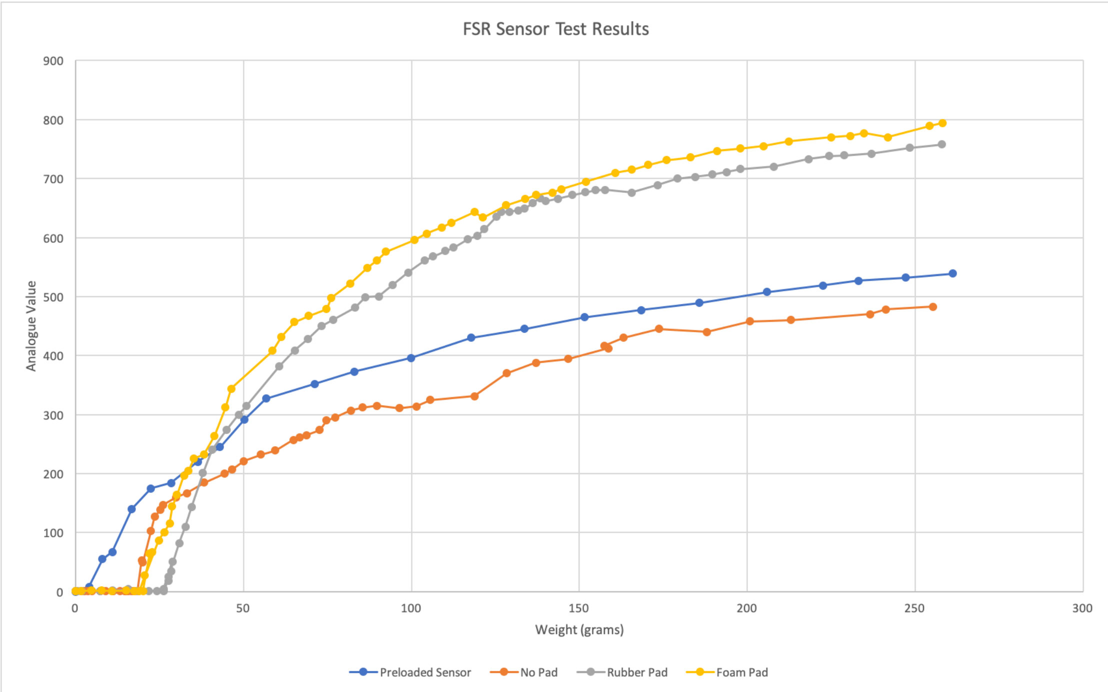


Fig. 10: Results of FSR bench test. Results show no readings below 25 grams across all three sensor coverings. Both the rubber and foam pads amplifying the FSR sensitivity, although the rubber pad requires a slightly increased load to gain readings (30 grams). The preload system provides a analogue reading with very little pressure being applied, 3.5-4 grams. Although the preloaded system is dampened in regards to the amplification of the signal.

Having this 'onset' sensitive was paramount to the success of the feedback method implementations. It is too late for the sensor to only deliver insightful information when an object is grasped. The concept of preloading the sensor was presented, referring to the internal application of stress to a surface. By preloading the FSR to 25 grams allowed for readings with a minuscule amount of force being applied to the sensor.

The design implemented to preload the FSR's can be seen in Fig. 11, a primitive design that uses tensioned rubber bands set on a rubber pad, allowing for a consistent force to be applied. This solution worked well and provided the operator with information in regards to discrete object interactions. Fig. 9 shows that the preload allowed for a sensor reading with only 3.5 - 4 grams being applied, a requirement for the sensing system.

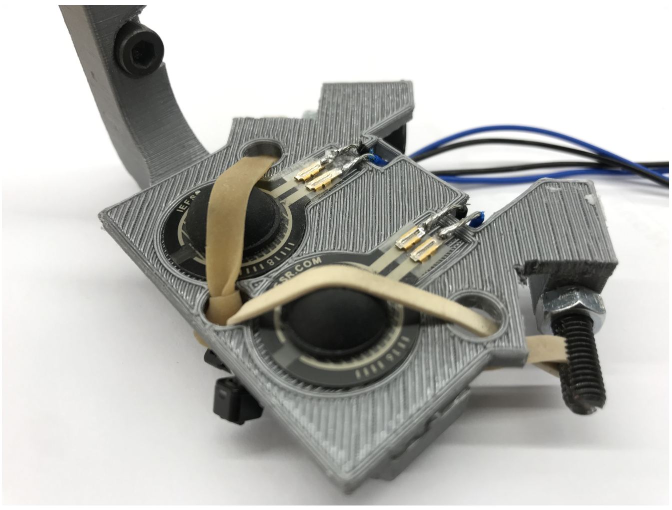


Fig. 11: FSR Preloading Implementation

While the FSR sensors allowed for sensory information in regards to contact surfaces and object interactions, there was no information in relation to the positioning within the remote environment, more specifically depth perception. Although it was initially a design choice to only use a single camera feed and provide limited depth perception, it became increasingly challenging without any additional feedback at all.

To combat this, an investigation was carried out into how information could be gained in regards to the positioning of the arm in relation to objects in the remote environment. Ultrasonic sensors were chosen as an appropriate choice of sensor. Ultrasonic sensors are an instrument that measure distance using ultrasonic waves. These sensors function by sending out a burst of ultrasound and listening for the echo when it bounces off of an object. The HY-SRF05 ultrasonic (Fig. 12) was implemented on the teleoperation system due to its non-contact range of 20 to 4000mm, economical value and simple implementation. The ultrasonic sensor was mounted on the underside of the gripper to provide the operator with useful information in relation to the distances in the remote environment.

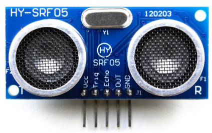


Fig. 12: HY-SRF05 Ultrasonic Sensor

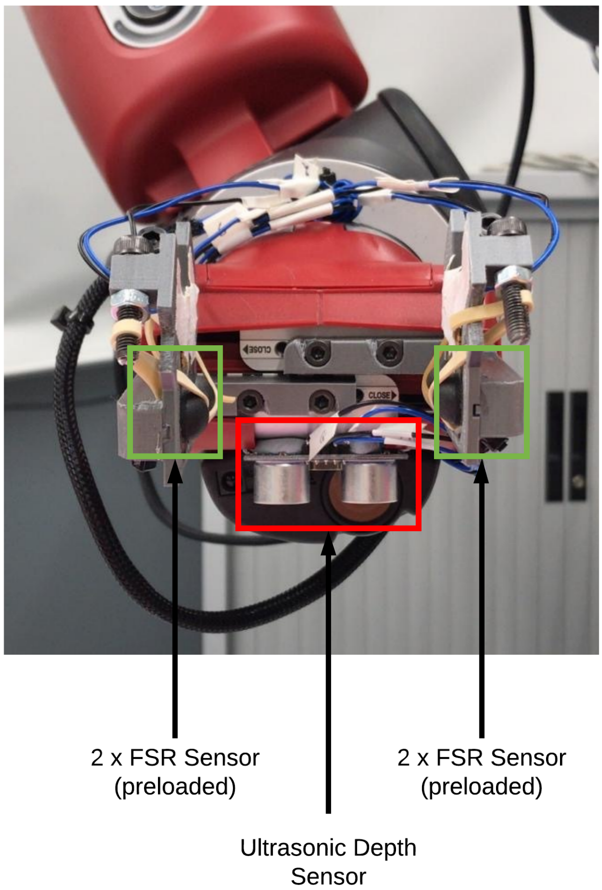


Fig. 13: FSR and Ultrasonic Configuration on Baxter Robot

Both the sensor systems (FSR and Ultrasonic) were implemented into individual ROS nodes using rosserial_arduino package, which allowed the use of ROS directly within Arduino IDE. Rosserial provides a ROS communication protocol that works over Arduino's UART. It allows microcontrollers to be a full fledged ROS node which can directly publish and subscribe to ROS messages (*ROS Wiki* n.d.).

3.3 Feedback Systems

Several alternatives are available to feed the sensor readings back to the user, the two detailed within this study are vibration feedback and visual cues.

3.3.1 Vibration Feedback

Using the openVR API, and more specifically the openVR Python bindings, it was possible to use the vibration actuators within the Vive controllers directly from ROS. Thanks to the previous implementation (Pfeiffer, 2018), it was possible to simply set up a publisher that advertised the vibration values, with each controller constantly subscribing to this topic.

Throughout the testing of the vibration implementation the vibration would not run constantly, which was a requirement of the feedback. This is problematic as by having intermittent vibration feedback confusion may be caused and the operator may be mislead. Although not confirmed, this is thought to be either a communication issue between the python bindings and the openVR SDK or a power consumption issue.

Following this, the decision was made to mount external vibration motors on the case of the Vive. This allowed for a constant strong vibration to be provided to the operator. For this implementation disc motors were used, a form of vibration motor that is 10mm in diameter and 2.7mm thick and used frequently in mobile phones, virtual reality equipment and haptic projects. Once again the ros_arduino package was used for communication to the microcontroller.

Although this implementation showed real potential with regards to the vibration itself it caused considerable issues relating to the tracking. Due to the Vive system being based not only on the infrared tracking but sensor fusion of the IMU within the device, a large amount of drift was caused due to the external noise and the effects on the accelerometer.

The next concept was to develop an arm mounted vibration solution. The initial thought was to mount the disc motors in the base of a 3D printed case which would be in contact with the surface of the arm. However, this did not function as anticipated because the vibration was not strong enough to make a noticeable indication. A second version of the concept was developed which utilised an ERM (eccentric rotating mass vibration motor). An ERM is an unbalanced mass on a DC motor which, when it rotates, creates a force that translates to vibrations. This was a much more obvious vibration and more noticeable on the surface of the arm. The main drawback of this implementation was that due to the current draw of the motor, it was not instant enough for some of the interactions within the remote environment, with the motor taking time to start to rotate and in turn vibrate.

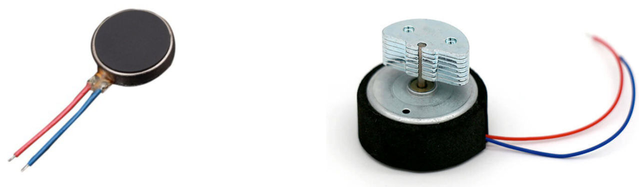


Fig. 14: Disc Motor (left) and ERM Motor (right)

A further concept was developed that consisted of vibration bands located at multiple locations on the arm. These vibration bands (Fig. 15) used a disc motor mounted on a metal plate which was secured using an elastic nylon material around the arm. The metal plate acted to amplify the vibration by changing the axis of rotation of the disk motor.

Fig. 15: Vibration band

The concept was implemented using a wireless microcontroller, ESP32 by Espressif. A low cost, low power, dual core, WiFi and dual-mode bluetooth chip. This allowed for wireless ROS communication with the host computer which subscribed to a topic that included all the vibration signals. The dual core feature allowed for the ESP32 microcontroller to retain the wireless connection whilst powering the motor drivers, without losing sync. To avoid overloading the ESP32 microcontroller, the motors were powered by a series of L298N motor drivers, a dual H-Bridge motor driver which allows speed and direction control of DC motors. The L298N was able to deliver a peak current of 2A without drawing current off the microcontroller itself.

This final implementation (Fig. 16) delivers a wireless vibration feedback system that provides strong vibration feedback to the operator without affecting the Vive tracking system, all housed in a wearable 3D printed construction. The system mounts two of the vibration bands on the top of the arm and two on the underside, these correlating to the sensors in the gripper and the ultrasonic under the arm. The vibration system having no gradient, either the vibration is on (meaning some form of physical interaction in the remote environment) or off.

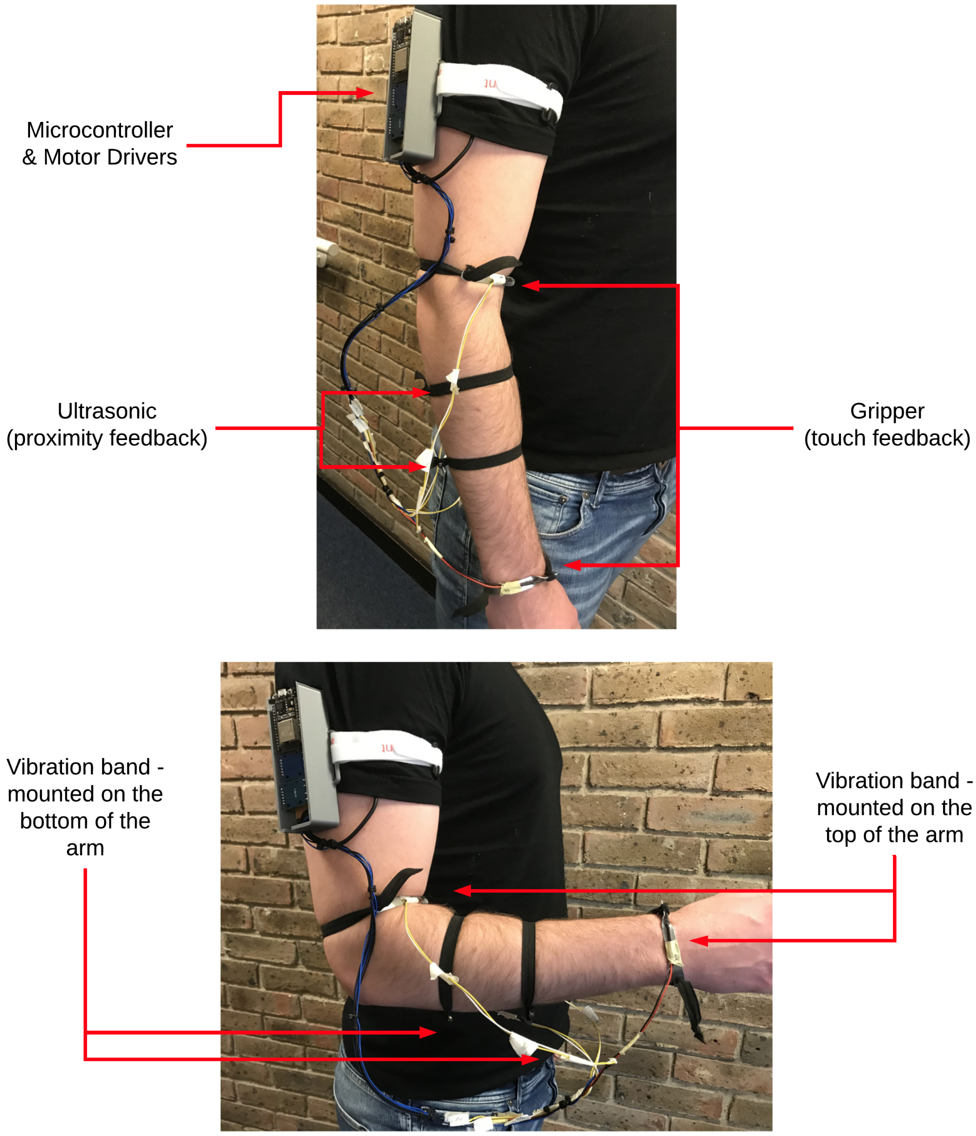


Fig. 16: Implemented Vibration System

3.3.2 Visual Feedback

The visual cue system needed to provide the operator with a graphical representation of any sensory information from the environment. The concept proposed, being a simple image of the gripper with zoned areas to show where pressure was present.

This design was implemented using QT, a free and open-source widget toolkit for creating graphical user interfaces. An additional QT ROS plugin allows the integration of ROS functionality into QT, allowing the user to subscribe and publish ROS nodes direct from a GUI.

The visual cue system simply subscribed to the sensory information topic and changed the colour of the zone according to a pre set threshold. Both the vibration feedback and visual cue systems were implemented with a binary approach. If sensory information was present or not present, this was represented by green and red cues in the visual cue system. The ultrasonic sensor only indicating a cue if the readings were below 100mm. This was considered the best approach as allowing for a gradient in relation to the sensory information was likely to cause confusion, especially within the visual cues. The visual cues were mapped to the four FSR sensors mounted within the gripper and indicated pressure on the sensor by changing the zone to red, whilst no pressure was present they remained green. Fig. 17 shows the final implemented visual cue system.

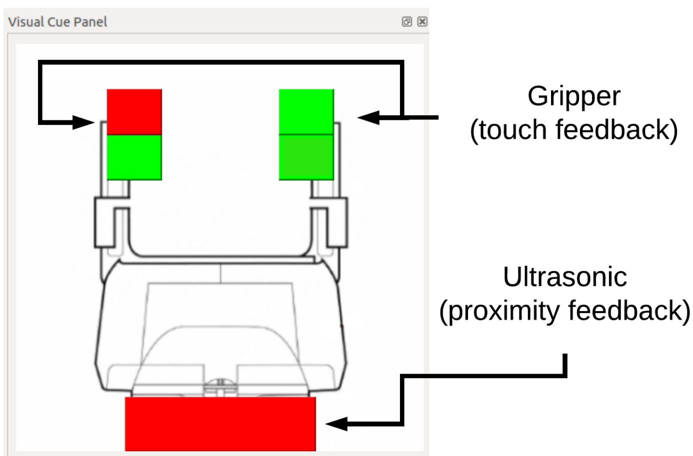


Fig. 17: Visual Cue System - red indicated pressure from FSR sensors or a proximity reading within 10cmm from the Ultrasonic sensor.

3.4 Control GUI

A GUI (graphical user interface) was developed for the sole use of the supervisor during the teleoperation. This GUI allowed for full control of the system and all the elements; including launching the HTC Vive tracking system, the operator starting the teleoperation control oneself, whilst also providing the supervisor with controls to activate and deactivate the sensory systems and multiple feedback methods. Additional functionality including an emergency stop button was implemented which allowed the supervisor to have complete control over the teleoperation system in order to reduce the risk of damage occurring to the robotic hardware. This teleoperation control window can be seen in Fig. 18.

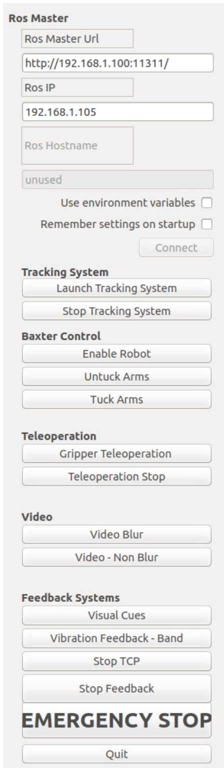


Fig. 18: Control GUI

3.5 System Architectures

3.5.1 Hardware Architecture

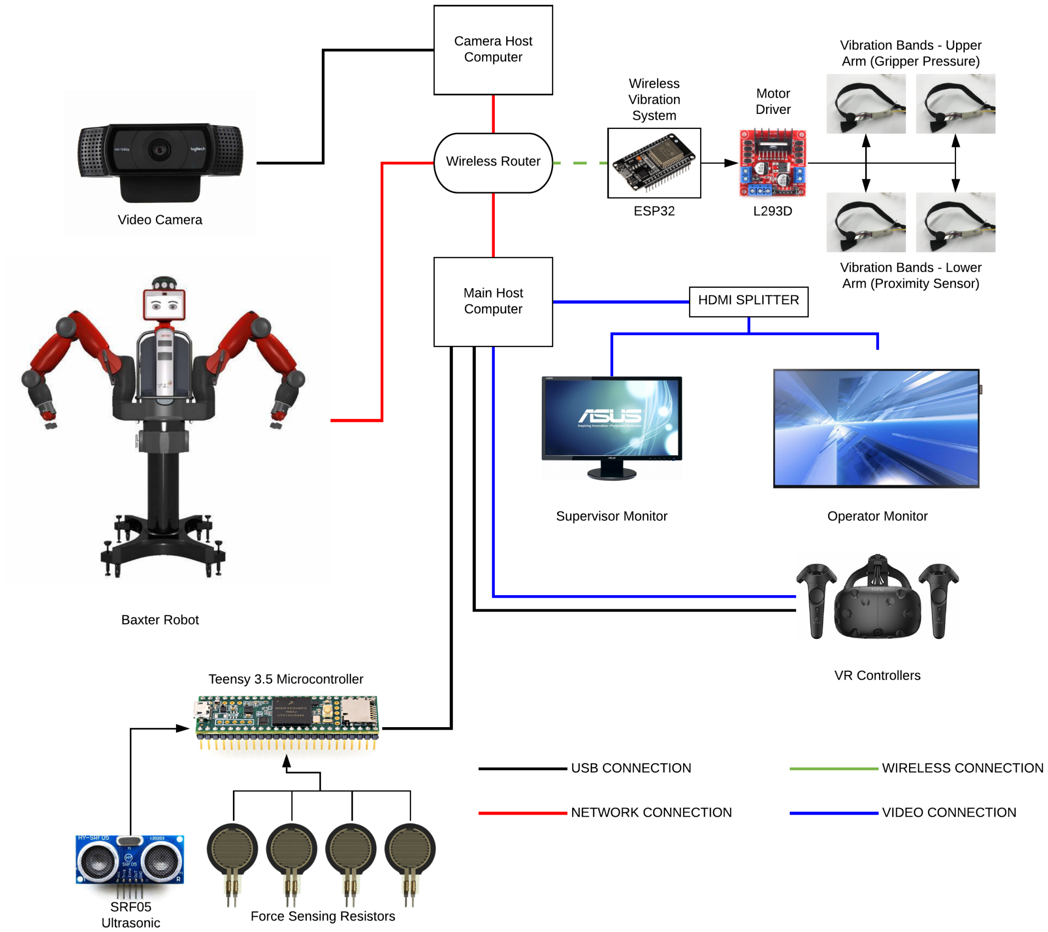


Fig. 19: Hardware Architecture

Fig. 19 shows the hardware architecture of the final implemented teleoperation system including the wireless vibration system. The graph provides a colour coding system as to the type of physical correction. The Baxter robot is connected via a wireless hub to the host computer, this wireless router is required to allow for the wireless vibration system to operate. The supervisor of the teleoperation tasks receives the same cameras feed as the operator through a HDMI splitter, allowing for greater supervision. The diagram also shows the micro controllers for both the sensory system and the wireless vibration system (including motor drivers and vibration actuators).

3.5.2 ROS Architecture

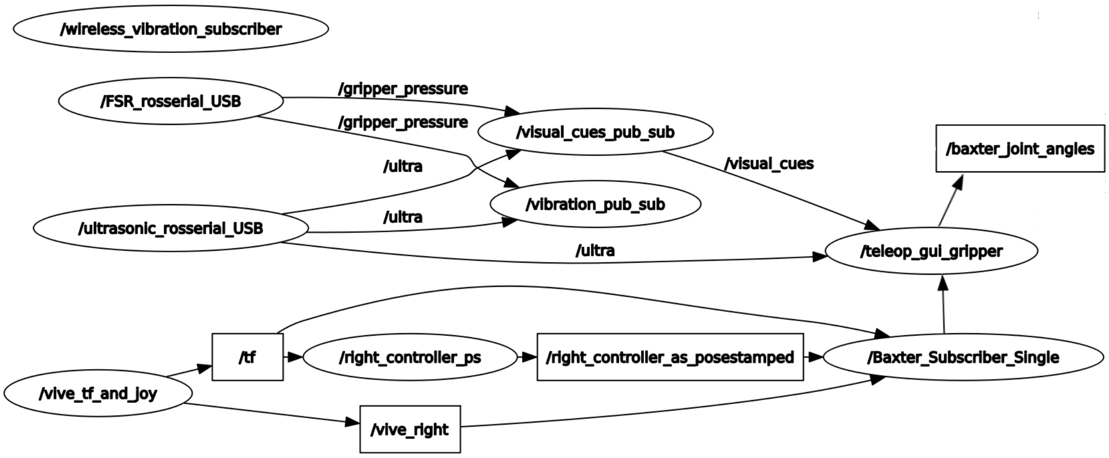


Fig. 20: ROS Architecture

Fig. 20 details the ROS communication of the associated notes within the teleopration system and provides an understanding of the system interaction. As is clear from the architecture there are two main sections of the ROS architecture, the first being the HTC Vive based tracking solution that initially provides the controller coordinate transform and the joystick information (in this scenario this is only button presses), these are then passed to the Baxter interface in the form of pose stamps. This Baxter node then provides the robot with exact joint angles in relation to the proposed end effector position. The second section of the ROS architecture deals with the sensor systems and integrated feedback systems, all controlled from a central GUI.

4 Experimentation and Results

In this chapter a test environment, associated study parameters and participant information are detailed. The implemented study developed allows the assessment of a teleoperation system and the associated impact of multiple sensory feedback methods.

4.1 Study Development

In order to get accurate and reliable results from the study it was imperative to have a clearly defined task. This meant that the task could be assessed in relation to the multiple measurable metrics that were considered important from the outset of the project. If the task is made too complicated, inconclusive results could be caused by having uncontrollable effects from variables unrelated to feedback methods. However, on the other hand, by making the task not challenging enough it would leave no requirement for the feedback method itself.

To combat this, initially the study phase of the project was started by implementing a pre study where the tasks themselves were considered, deciding on the varying factors and parameters that would remain constant throughout. It was key to remember throughout this process that it would be a study made up of voluntary participants, needing to be streamlined and not lasting longer than an hour.

The first major decision that needed to be made was the remote environment the participants would be teleoperating in, and how measurable data could be collected from interactions with this environment. A board with zoned areas was developed and implemented, allowing objects to be moved and manipulated within a measurable space allowing consistently same size areas.

The tasks themselves were always intended to be as challenging as possible, although it was important to make it to a level that untrained individuals could at least complete some of each task, whether that be simply picking up an object or moving an object from a to b would allow for results in regards to errors rates. To combat this a static approach was implemented in regards to the environment, by 'static' we are referring to the changeable variables between the tasks themselves. The zoned area would remain the same between tasks, as would the distance in relation to the base of the robot and the height of the table itself. Fig. 1 shows the physical parameters defined for the remote teleoperation environment, Fig. 2 shows the real world set up.

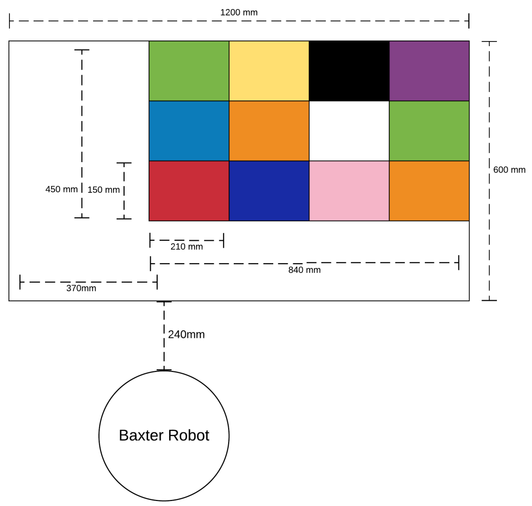


Fig. 1: Layout parameters of remote environment

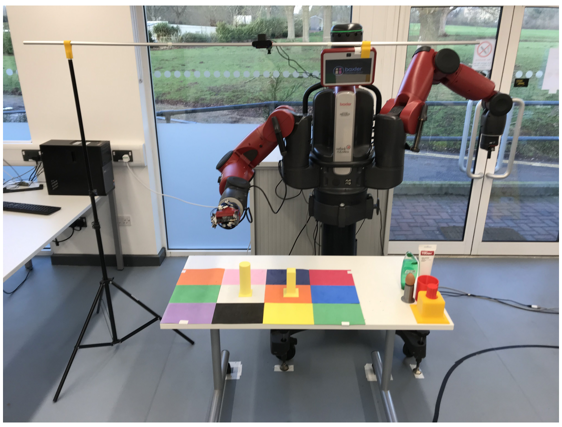


Fig. 2: Real world remote environment

It was paramount that all participants had consistent dimensions in relation to the camera display and trackers whilst control the teleoperation system. The screen was fixed at a height of 120cm, with the operator being set back at 200cm and light house trackers set aside 120cm from the centre of the screen. The point in which the operator had to stand was marked with a cross, the height of the controller was not relevant as this was calibrated at a height found comfortable by the operator. Fig. 3 shows the physical dimensions of the control environment, Fig. 4 showing the real world layout.

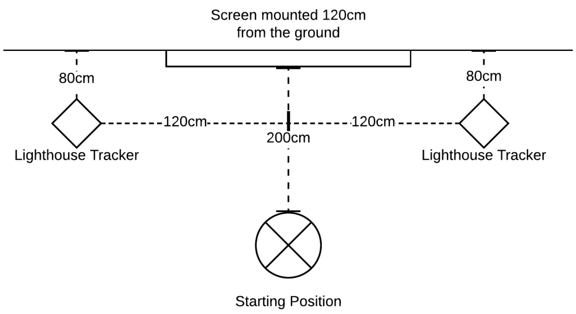


Fig. 3: Layout parameters of remote environment

Fig. 4: Real world control area

The tasks were required to be generic, real world manipulation tasks, interacting with day to day objects. This would allow for no formal training as participants would not be undertaking a specific task with unfamiliar objects or unknown operations. This was mainly due to not having a specific research application (for example robot-assisted minimal invasive surgery) unlike other studies. The general approach was to do a series of pick and place tasks, moving certain objects into the zoned areas. By monitoring the time between picking up/releasing of objects along with the error rate, a greater understanding and insight of the impact the feedback methods have would be gained.

A range of objects were considered for the tasks within the study. The main requirement being to ensure variation in the objects as a whole. In relation to size, weight, shape, surface material and appearance (Fig. 5 showing the finally selected objects, Table 4.1 providing a brief description of the task objects. An effort was made to select objects with various levels of rigidity, Fig. 6 shows a selected object and the level of deformation with minimal pressure. Although at the core of the task would be a pick and place approach it was important to have interactions with elements of higher complexity. This would allow for a greater understanding of the feedback across a range of manipulations.

Fig. 5: Task Objects

Fig. 6: Deformation of Object 1

Object	Description	Material	Weight (grams)	Comment
1	Carton	Plastic	340	Challenging shape, easy to deform
2	Bottle	Plastic	286.5	Challenging shape, rigid
3	Egg	Rubber	68.7	Small, uneven
4	Bar	Plastic	37.1	Lightweight, uneven sides
5	Peg	Plastic	77	Circular, rigid

Table 4.1: Object Descriptions

Task 1 (Fig. 7) was the initial task for each participant to undertake; simply picking up and moving object 2 from the black zone directly into the green zone, followed by picking up object 1 in the yellow zone and moving it in the white zone. The route in which the objects were moved does not matter, participants could go in whichever route they preferred across all three tasks.

Task 2 (Fig. 8) was slightly more advanced and required a higher level of accuracy and understanding of the remote environment. Initially moving object 3 in the orange zone (from a 10cm platform) into the blue zone, then picking up object 2 in the white zone and placing it in the red zone (this movement requiring a complete orientation change of the end effector) and finally the most challenging part of the task; picking up object 5 from the green zone and placing it in the hole within the black zone (peg in hole task).

Task 3 (Fig. 9) was the most complex and challenging manipulation task that the study required. Participants were required to move a parallel bar (object 4) from one platform to another (the platforms shown in Fig. 10). With both platforms holding the parallel bar in a semicircle, allowing the bar to rotate with a small force applied and in turn increasing the level of complexity. This task was implemented to really push the participants in relation to physical and frustration level. Throughout the study all participants would be informed to complete the tasks as fast as possible, whilst avoiding failure of tasks.

All tasks would be recorded using external cameras, both the remote environment and the operator being recorded throughout. This was implemented to allow accurate results analysis in relation to time of completion and error rate. Time of completion refers to the overall time from the start to the end of the task. The error rate would be recorded which was considered to be object interactions that lead to either a drop or knock over, additionally the number of resets were recorded. An object was reset if an object was dropped, knocked over or placed in the wrong zone.

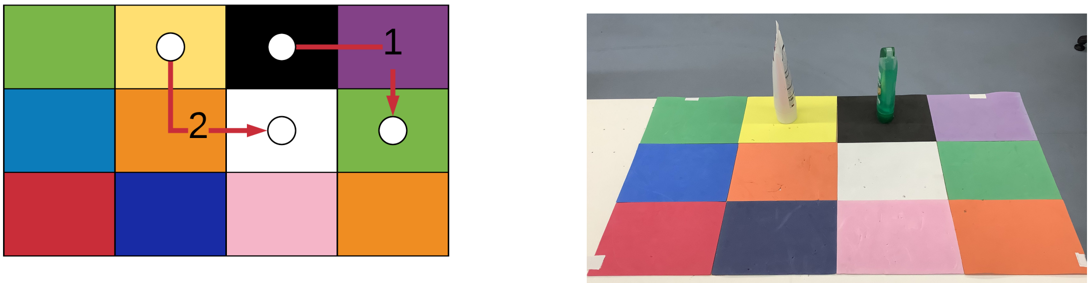


Fig. 7: Task 1 Layout - Study steps (left), real world board and objects(right)

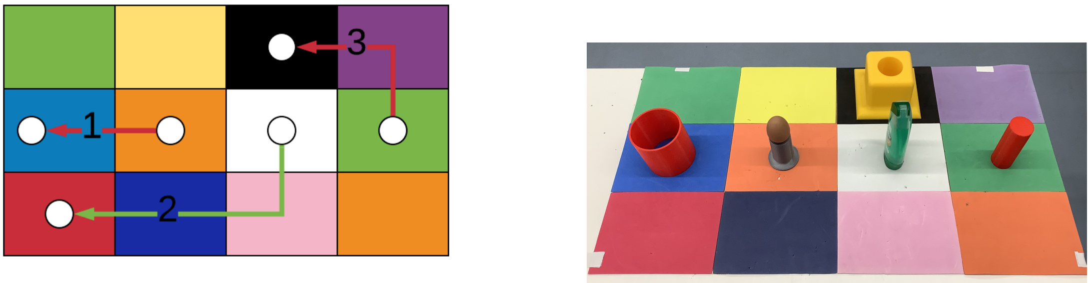


Fig. 8: Task 2 Layout - Study steps (left), real world board and objects(right)

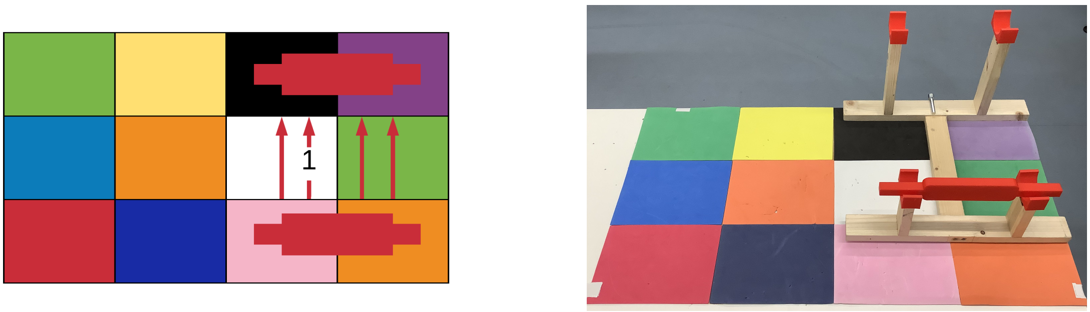
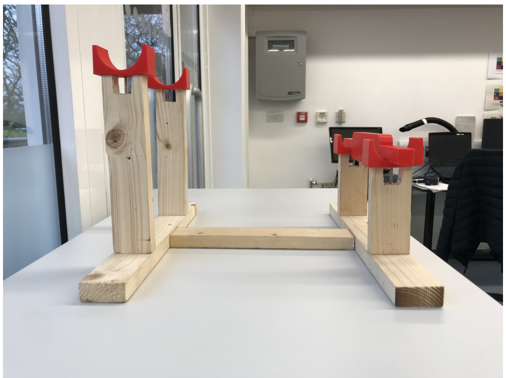


Fig. 9: Task 3 Layout - Study steps (left), real world board and parallel bar (right)

Each participant would be allowed a 3 minute familiarisation period before starting the task, where two objects would be provided. These objects being specific for this period and not used in any of the actual tasks (shown in Fig. 11. The practice objects being plastic, rigid, 3D printed objects with generic shapes to follow for easy manipulation during the initial learning period. There was no specific task outlined within this time period. This was to allow participants to move the objects around the zoned areas and gain an understanding of both the controller, physical limits of the robot and the environment they were operating



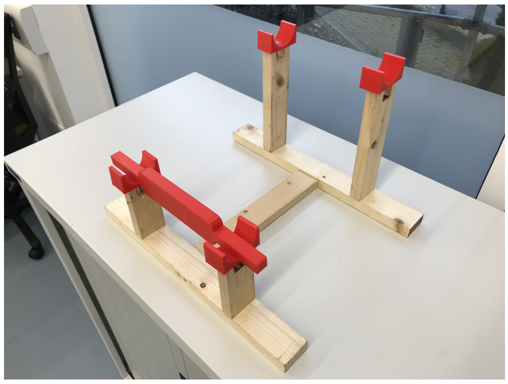


Fig. 10: Parallel Bar Apparatus

in. Neither visual or vibration feedback were provided during the initial period, only a camera feed.

All physical physical dimensions of task objects can be found in section 3 of the appendix.

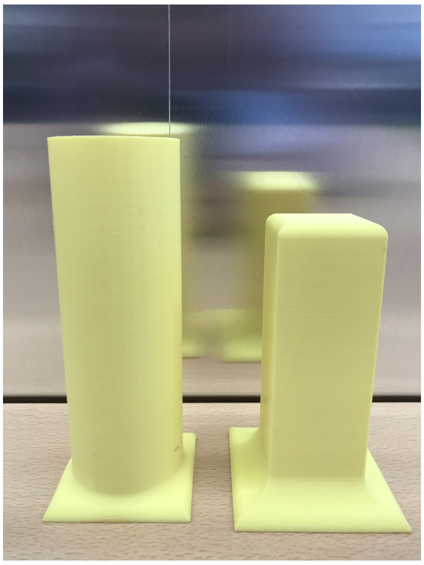


Fig. 11: Practice Objects

4.2 Measurements

The study is set out on three individual tasks that endeavour to push the operators manipulation skills within the teleoperation scenario, these three tasks are to be undertaken in a fixed order. Due to this fixed task ordering along with three feedback method conditions (no feedback, visual feedback and vibration feedback) there are 6 permutations required in relation to feedback ordering (table 4.2). By allocating participants randomly into one of the six sets allows for accurate results across the study as a whole, if the study had implemented the feedback systems on specific tasks throughout we would have a restricted area of investigation and analysis of the individual feedback methods.

Set Number	Task 1	Task 2	Task 3
1	No FB	Vibration FB	Visual Cues
2	Visual Cues	No FB	Vibration
3	Vibration FB	Visual Cues	No FB
4	No FB	Visual Cues	Vibration FB
5	Visual Cues	Vibration FB	No FB
6	Vibration FB	No FB	Visual Cues

Table 4.2: Set Permutations

Each task would be undertaken three times with the same feedback method. The overall time of completion, fastest attempt and average time across all three attempts being recorded. The error rate of object interactions would also be recorded. With all the analysis completed after the task (from video recordings) to ensure accuracy and to reduce administration errors. An example would be a participant doing task 1 three times with vibration feedback, task 2 three times with visual cues and the final task three times with no feedback.

As well as recording the time of completion and task error rate, participants were asked to fill in a questionnaire before starting the study. This was used to identify participants age, gender, dominant hand, any eye/medical conditions along with their level of technological competence and understanding of robotics (self assessed). This would allow for a consideration of any demographics that were present within the study data.

Furthermore, following a full set of three runs on teach task, the NASA-TLX (Task Load Index) was used to analyse the perceived workload of each task and the impact of associated feedback method. The NASA-TLX is a widely used assessment tool that measures the perceived workload of a particular task (Group et al., 1987). This is gained by measuring the global workload across six subscales: mental demand, physical demand, temporal demand, effort, frustration and performance. Descriptions below -

Mental Demand

How much mental and perceptual activity was required? Was the task easy or demanding, simple or complex?

Physical Demand

How much physical activity was required? Was the task easy or demanding, slack or strenuous?

Temporal Demand

How much time pressure did you feel due to the pace at which the tasks or task elements occurred? Was the pace slow or rapid?

Overall Performance

How successful were you in performing the task? How satisfied were you with your performance?

Effort

How hard did you have to work (mentally and physically) to accomplish your level of performance?

Frustration Level

How irritated, stressed, and annoyed versus content, relaxed, and complacent did you feel during the task?

Participants were asked to provide a weighting of each individual subscale, in relation to which is more relevant to workload of the task. This is collected using pairwise comparisons, the number of times a subscale is selected being the subscale weighting. Following this, participants are asked to provide a rating of their workload along each of the six dimensions via a scale ranging from 0 (low) to 100 (high) for the first five dimensions, and 0 (perfect) to 100 (low) for performance. The raw TLX values are multiplied by the subscale weighting for each dimension and then divided by 15 to get a workload score from 0 to 100, this being the overall task load index. Furthermore, the 'raw TLX' is used to get a frustration value across tasks and feedback methods. The Nasa-TLX data being collected using the official nasa-TLX application on an Apple Ipad (Nasa, 2017). Allowing for all the calculations to be made automatically, reducing analysis time.

Throughout the study all tasks were recorded using rosbag, a set of tools for recording and playing back to ROS topics. This allowed complete playback of every aspect of the tasks after completion with potentially further investigation in relation to learning curves and route planning of such teleoperation systems. The rosbag tool was set up to record almost all the elements of the teleoperation system including the feedback methods, controller positions, joint angles of the robot and end effector position of the robot.

4.3 Participants

The study was made up of 24 participants (17 male, 7 female) with ages ranging from 21 to 62 (M = 27.70 , SD = 10.72). Level of self-assessed technological competence (measured between 0 and 100) varying between 35 and 95 (M = 65.83 , SD = 17.17). Knowledge of robotics and teleoperation systems (also self assessed), measured between 0 and 100 and ranging from 5 and 90 (M = 37.70 , SD = 27.18). The study used participants with mainly dominant right hands, with a split of right = 18, and left = 4.

There was an exact split between participants that were students and staff based at Wheatley Campus and participants recruited externally, 12 of each group. This was a deliberate decision to avoid getting a specific demographic of person. Furthermore, students studying robotics where not allowed to take part in the study (due to have prior knowledge and understanding of such systems) and an effort was made to not use participants from computer science courses, the aim to get a demographic range of people. Externally sourced participants were not selected in any specific way and came from a range of jobs and technological competency levels.

Participants were provided with a comprehensive information sheet before agreeing to partake in the study, the information sheet detailing the teleoperation system, the tasks they would be undertaking along with any risks associated. Participants were also provided with information regarding data storage and how their data would be kept safe, these forms presented to all participants can be found in section 2 of the appendix.

The participants were then shown the teleoperation system and the remote environment, along with a demonstration of the robotic control. Following this the participants were asked to fill out a consent form and 3 minute familiarisation period was started.

All participants were anonymised during the study and supplied with a unique ID number.

5 Data Analysis and Research Findings

This chapters details the results found of 24 participants within the teleportation study.

5.1 Results

A table of all the results can be found in section 1 of the appendix.

5.2 Participant Comments

Comments made by participants after completing three tasks with all feedback methods.

216
'Feedback systems useful. All tasks challenging. Needed more time to learn the general control of the teleoperation system'

430
'Vibration was preferred. Not physically challenging but very demanding in regards to mental and temporal. More practice would help a lot'

53
'Last task was a lot harder than others. No depth perception, not as bad for tasks 1 and 2. Used the visual cues, vibration useful judging the height of objects'

517
'Vibration helped and was more intuitive than visual cues. Depth sensing useful. Would have been better to have the feedback whilst learning the task. As the distance to table was learnt'

199
'Frustrating last task. Task driven. Tracking and movement frustrating as expectations of movement aren't always matched. Depth sensing useful. Gripper sensing useful for vibration.'

5.3 Results Analysis

5.3.1 Overall Task Time

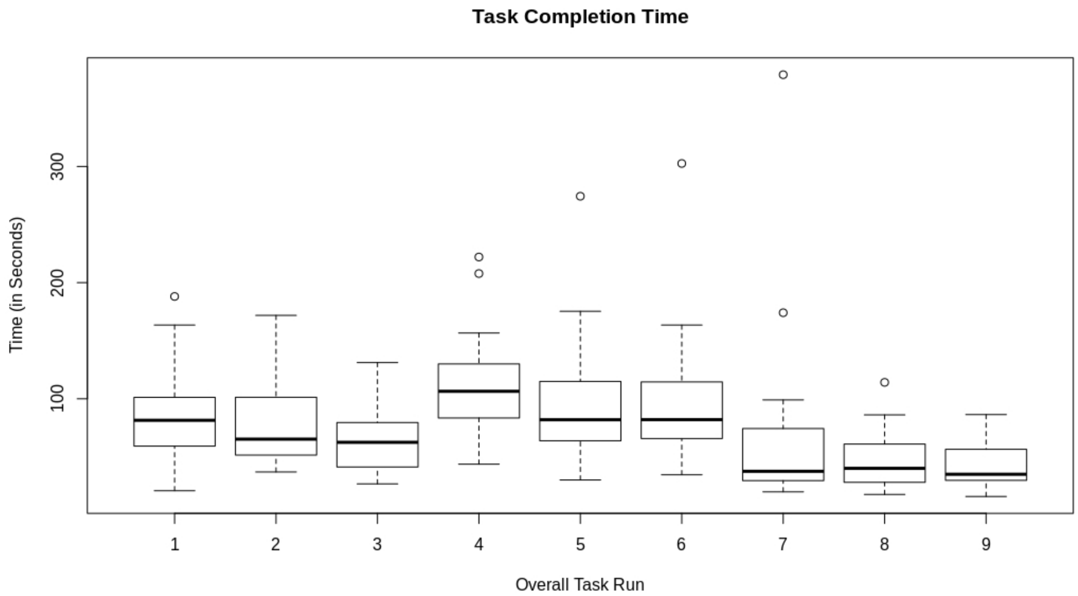


Fig. 1: Task Completion Times - showing all data collected in relation to overall completion times across all three tasks. 1-9 refers to the overall task run with task one being (1-3), task two being (4-6) and three being (7-9). The plots present a overall learning affect from participants first attempt of a task compared to their last.

Fig. 1 shows all the data recorded in relation to 'time of completion' of all three tasks. Task run refers to the overall attempt of each participant, 1-3 being Task 1, 4-6 being Task 2 and 7-9 being Task 3. The box plot provides a graphical representation of the distributed data recorded and shows the minimum and maximum overall times recorded (shown by the top and bottom line). The box (or interquartile range) shows the middle two quartiles of the data set; the first quartile (or 25th percentile) is the middle value between the smallest number and the median of the dataset, the third quartile (or 75th percentile) is the middle value between the median and the highest value. The horizontal line within the box shows the median value, the middle value of the dataset.

Any outliers within the dataset are shown outside of the top and bottom line and represent a data point that is significantly different from the majority of the dataset.

The data set shown in Fig. 1 is irrespective of feedback methods and aims to give an overview of the general learning effect of the teleoperation tasks, regardless of any feedback method. As is clear from Fig. 1 there is a large amount of variance in the completion times across the experiment as a whole. Although what is evident is the general reduction in the median for each task between the initial attempt and the final attempt. Thus implying a general learning effect throughout the tasks for the participants.

As hypothesized, participants completed the teleoperation tasks faster on the third and final attempt of a task compared to the initial attempt. This is confirmed by undertaking a sign test of the dataset as a whole, this method allows individual sub sets to be created for a third task attempt completion time that is less than the first attempt, these sub sets creating a binary variable for each task as to the number of third attempts faster than first attempts. Using these binary variables it is possible to perform a statistical sign test on the sub sets. A sign test test produces a p-value (probability value) to help determine a level of significance of the data. The p-value is the probability of the null hypothesis being true. The null hypothesis being equal medians which implies a 50/50 split between completion times slower in the 3rd attempt and completion times faster in the third attempt, the alternative hypothesis being that there is not a 50/50 split.

Assuming the null hypothesis is true; the smaller the p-value, the stronger the evidence in favour of the alternative hypothesis. By having a significance level of 5% or lower (< 0.05) the findings can be considered significant and the null hypothesis can be rejected. Furthermore, a larger p value, with a threshold level of 0.05, indicates weaker evidence against the null hypothesis meaning the null hypothesis cannot be rejected and the findings are not significant.

A statistical sign test against the Null-hypothesis of equal medians confirms the significance of this finding (Task 1 $p=0.064$, Task 2 $p=0.023$, Task 3 $p=0.015$). It was possible to use a sign test due to the presence of pairwise data.

The findings in relation to the hypothesised learning effects show that participants were able to complete the task faster on the third attempt compared the the first attempt, this can be confirmed from Table 5.1 demonstrating that for task 2 and 3 the results are significant. Although for task 1, the result are marginal due to a p value of 0.06391. As the majority shows a significant results it is possible to draw the conclusion that participant did perform fast in their third task attempt compared to their first.

Fig. 2, Fig. 3 and Fig. 4 further break down the overall completion time in relation to the feedback methods; red being no feedback, green being visual

Task Learning Effect	Task Number	No./24	P-Value
3rd attempt < 1st attempt	1	17	0.06391
3rd attempt < 1st attempt	2	18	0.02266
3rd attempt < 1st attempt	3	16	0.01516

Table 5.1: Binomial Test Results - Task Learning Effect

cues and blue being vibration feedback. Contrary to the clearly pronounced learning curve, no significant difference are found in comparison of different feedback methods. This being demonstrated by the boxplots themselves, there is no significant result from the implementation of the feedback systems in relation to the completion time. This goes against the predicted hypothesis that considered both visual and vibration feedback to have a positive influence on the overall completion time of a task. All feedback methods had wide ranging data sets along with a large amount of variance for each task and task attempt. The results section focuses on median values as this allows for a greater understanding and overview of the data as a whole.

In some cases, specifically Task 3, the feedback systems are measured to have a negative impact on the overall completion time of the task, although results are not in a statistically significant range. Along with this, participants performing tasks with vibration feedback had no reduction in completion time compared to visual cues, this further rejects the hypothesis initially outlined.

As participants performed each task with a specific feedback method there is not pairwise data available. Due to this, a T-Test is implemented to confirm if the findings were significant. Unlike a binomial test, T-testing is used to determine significant differences between the two groups which may be related in certain features. The results from the T-Test can be found in Table 5.2, which shows across all the feedback methods and tasks the null hypothesis could not be rejected. Therefore the results show that visual and vibration feedback have no impact in reducing the overall task time of the teleoperation task. Furthermore, it is shown that vibration has no reduction in overall task completion time compared to visual cues. These finding going against the original hypothesis.

Additionally the p-values generated within the T-test to be considered conclusive, the datasets must be gaussian (or normally) distributed. By using a Shapiro-Wilk test on the individual data sets (no feedback, visual cues and vibration feedback for task one, two and three), the conclusion can be drawn that all 9 datasets are not normally distributed with all the p-values being less than 0.5. The null hypothesis for a Shapiro-Wilk test assumes the data is normally distributed, by having a p-value less than 0.05, the null hypothesis (that the data is normally distributed) must be rejected.

Overall Completion Time	**Task Number**	**No./24**	**P-Value**
Visual < No Feedback	1	14	0.8415
Visual < No Feedback	2	14	0.5988
Visual < No Feedback	3	16	0.4287
Vibration Feedback < No Feedback	1	13	0.8453
Vibration Feedback < No Feedback	2	12	0.3382
Vibration Feedback < No Feedback	3	13	0.1619
Vibration Feedback < Visual Cues	1	11	0.7047
Vibration Feedback < Visual Cues	2	15	0.5698
Vibration Feedback < Visual Cues	3	11	0.3331

Table 5.2: T-Test Results - Overall Completion Times

Feedback Method	**Task Number**	**P-Value**
No Feedback	1	0.3406
Visual Cues	1	0.005167
Vibration Feedback	1	0.06506
No Feedback	2	0.0464
Visual Cues	2	0.01185
Vibration Feedback	2	0.001942
No Feedback	3	4.01e-08
Visual Cues	3	0.0001725
Vibration Feedback	3	0.0004553

Table 5.3: Shapiro Wilkes - Feedback Set Distrubtion

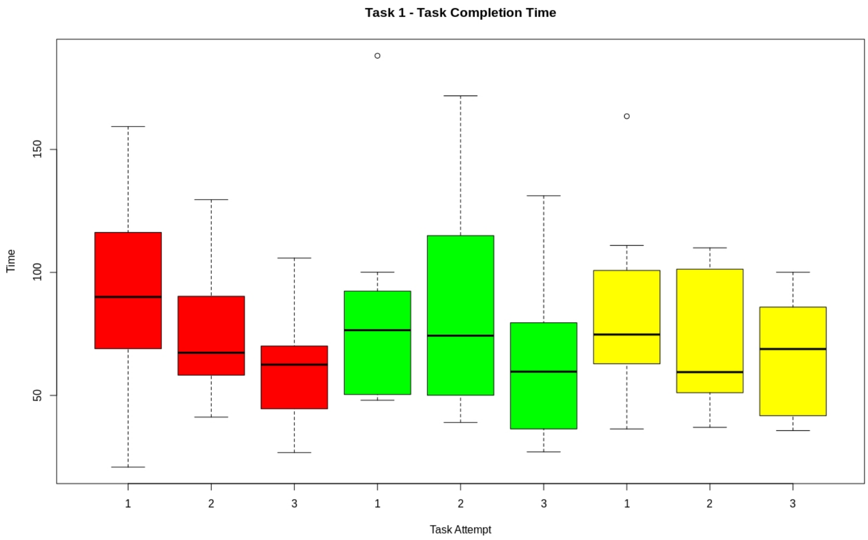


Fig. 2: Task 1 Completion Times - Feedback methods labelled red (no feedback), green (visual cues) and yellow (vibration feedback). Results show no significant reduction in overall completion time with the addition of both visual cues and vibration feedback.

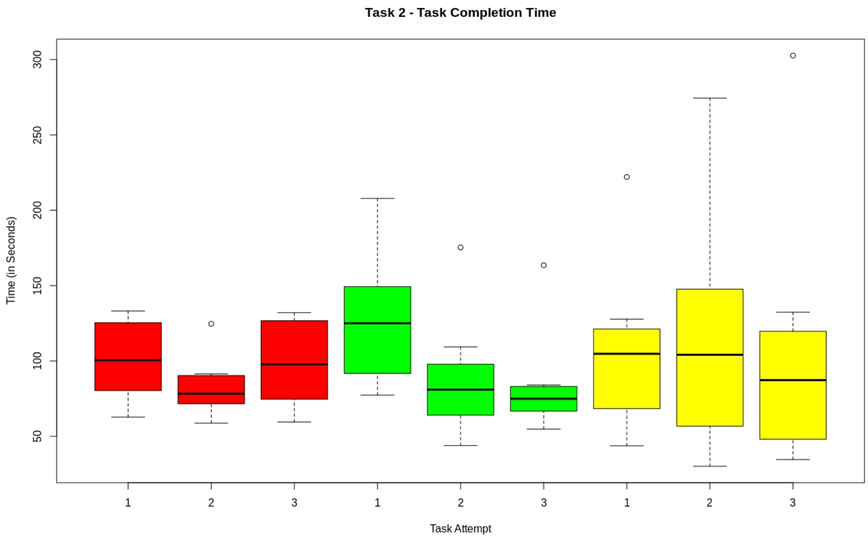


Fig. 3: Task 2 Completion Times - Feedback methods labelled red (no feedback), green(visual cues) and yellow (vibration feedback). Results show no significant reduction in overall completion time with the addition of both visual cues and vibration feedback.

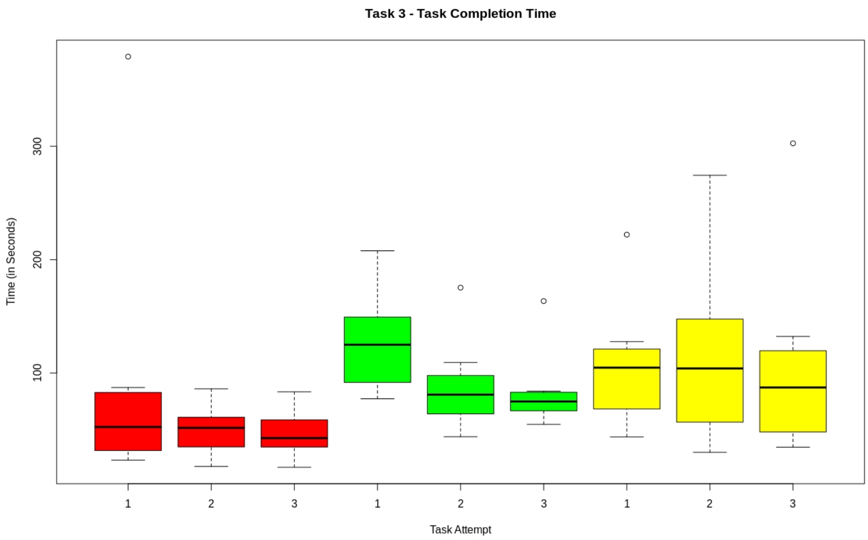


Fig. 4: Task 3 Completion Times - Feedback methods labelled red (no feedback), green(visual cues) and yellow (vibration feedback). Results show a increase in the task completion time with the addition of visual cues and vibration. This may be due to the task itself having a higher level of complexity.

5.3.2 Task Error Rate

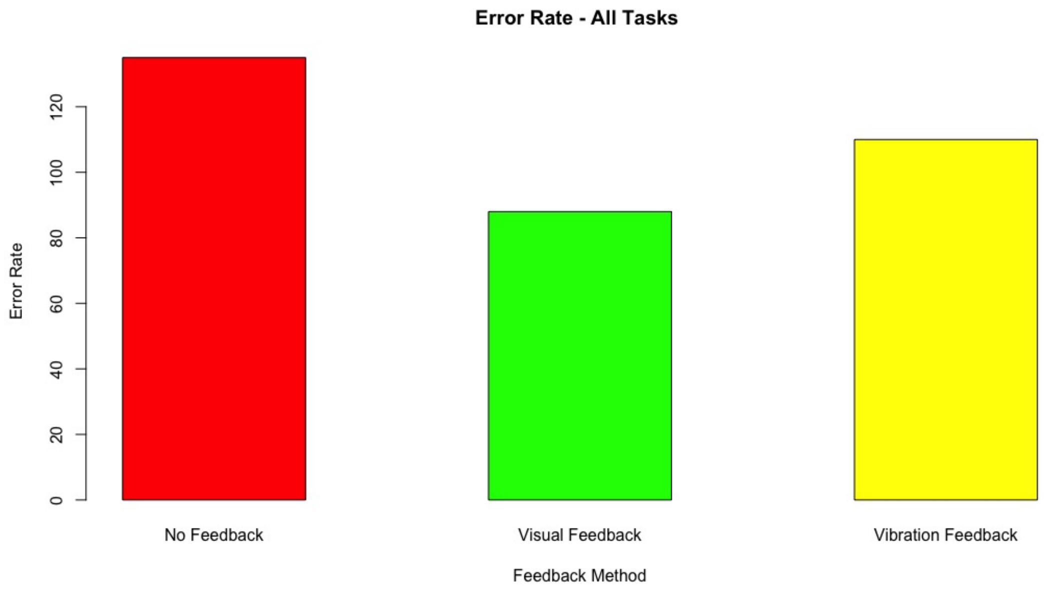


Fig. 5: Error rate across all tasks with the feedback methods being labelled red (no feedback), green(visual cues) and yellow (vibration feedback). Plots show a small reduction in error rate with the application of vibration feedback but a larger reduction with the addition of visual cues.

Fig. 5 gives an overview of the error rate across all three tasks, separating the dataset out into the three feedback conditions; no feedback, visual cues and vibration. Error rates from object knock-overs and object-drops where 1.88 per run for no-feedback, 1.22 for visual feedback, and 1.53 for vibration feedback.

As is clear from the Fig. 5, both visual cues and vibration feedback reduced the overall tasks error rate, with visual feedback reducing this lower than vibration feedback. This can be further observed within Fig. 6, Fig. 7 and Fig. 8 which indicates across all three tasks that vibration feedback and visual cues have consistently lower error rate, with visual cues being typically lower than vibration.

Due to the dataset itself, not being made up of pairwise data, a T-Test was implemented to confirm if the findings were significant. Unlike a binomial test, T testing is used to determine significant differences between the two groups which may be related in certain features. The T test results can be seen in Table 5.4, which present a significant margin (p=0.003) between no-feedback and visual-feedback, but not vibration feedback (p=0.18).

The t-test operates based on a Gaussian distribution assumption that was not confirmed valid on the data. A Shapiro-Wilk test was used on the individual data sets (no feedback, visual cues and vibration feedback), a conclusion being drawn that all three datasets are not normally distributed with the p-values for the no feedback condition being 2.766e-05, the visual feedback condition being 5.594e-07 and the vibration condition being 5.594e-07.

Task Error Rate	P-Value (T-Test)
Visual < No Feedback	0.002887
Vibration < No Feedback	0.1764
Vibration < Visual Cues	0.1864

Table 5.4: T-Test Results - Task Error Rate

For this reason we must conclude that, regardless of having a significant finding in relation to visual cues reducing the number of error rate compared to no feedback, we are not able to get fully conclusive results due to the dataset not being normally distributed. These results are contrary to the predictions made across multiple hypothesis, more detail regarding these hypotheses can be found in section 2.

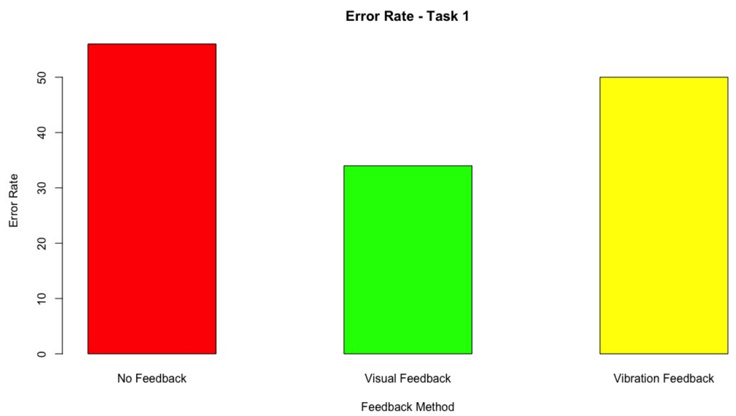


Fig. 6: Task 1 - Error Rate Bar Plot. Feedback methods labelled red (no feedback), green(visual cues) and yellow (vibration feedback)

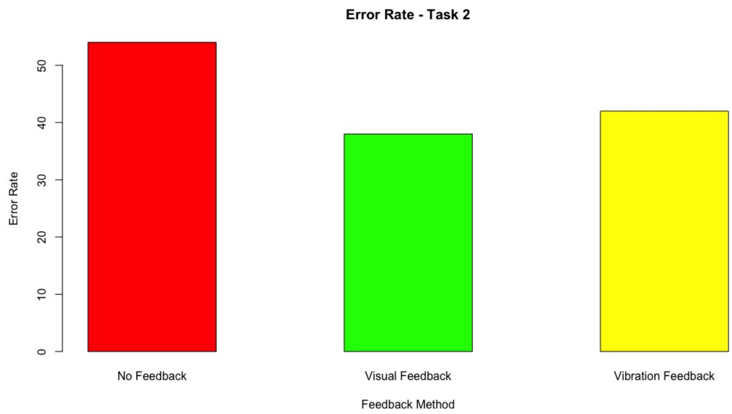


Fig. 7: Task 2 - Error Rate Bar Plot. Feedback methods labelled red (no feedback), green(visual cues) and yellow (vibration feedback)

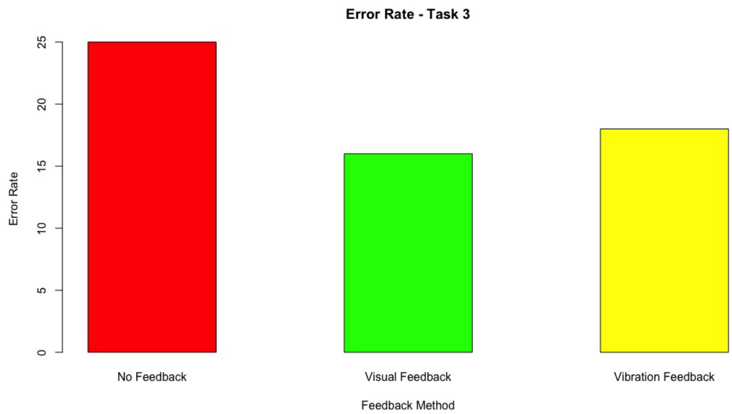


Fig. 8: Task 3 - Error Rate Bar Plot. Feedback methods labelled red (no feedback), green(visual cues) and yellow (vibration feedback)

5.3.3 Task Load Index (TLX)

The results from the Task Load Index in relation to individual tasks can be seen in Fig. 10, 11 and 12. This looks at the perceived workload of the task in relation to the specific feedback method. As is clear from all three boxplots, and specifically Task 3, vibration significantly reduces the median value of perceived workload in comparison to the no feedback condition. Additionally, the variance in the data of vibration is consistently reduced compared to that of the no feedback condition. With limited outliers across all feedback methods, this would indicate a relatively concrete finding with regards to the consistency of the results.

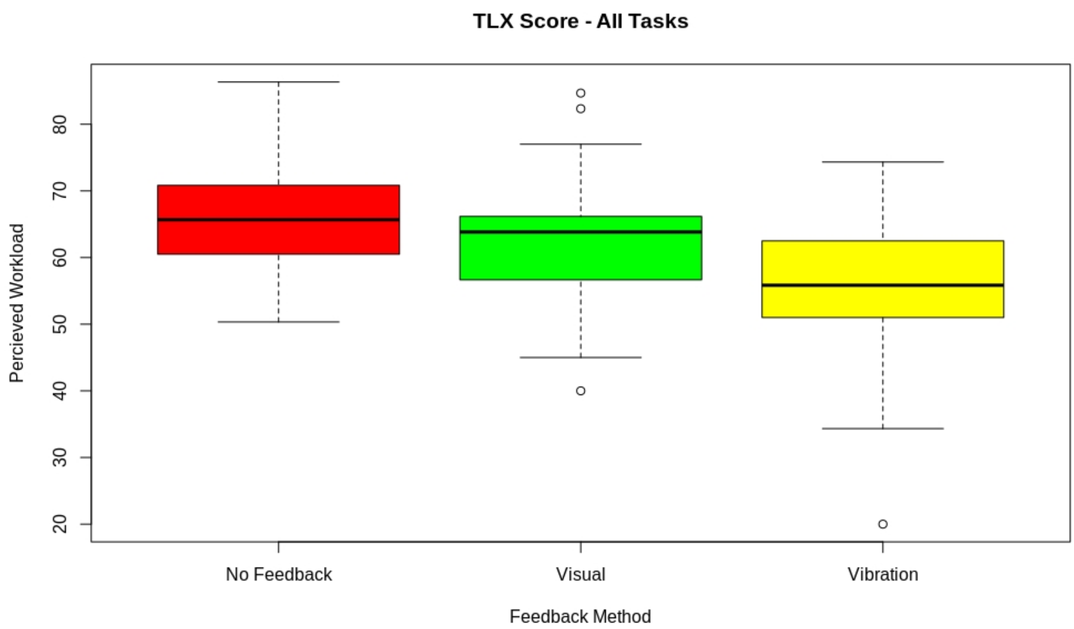


Fig. 9: TLX Overall Scores - Feedback methods labelled red (no feedback), green(visual cues) and yellow (vibration feedback). Results showing a consistent reduction in perceived workload with the addition of vibration and visual feedback, across all three tasks undertaken by participants.

By implementing a sign test and binary variable of the related sub sets, vibration feedback being less than no feedback, visual cues being less than no feedback and vibration feedback being less than visual cues, it is possible to gain an understanding of the reduction to the perceived workload of all the tasks. Furthermore by implementing a binomial test across these sub sets, significant findings can be searched for in relation to the assumption that perceived workload is lower with the addition of both feedback conditions. The results from this binomial test can be found in Fig 5.5.

Perceived Workload (TLX)	**No./24**	**P-Value**
Visual < No Feedback	14	0.5413
Vibration < No Feedback	22	3.588e-05
Vibration < Visual Cues	18	0.02266

Table 5.5: Binomial Test Results - TLX

The p-values show that visual cues reduce the perceived workload compared to no feedback, across all three tasks. However, this is only marginal and not a conclusive result. A significant result is found with regards to vibration feedback, reducing the perceived workload (in comparison to no feedback) along with vibration reducing the perceived workload compared to visual cues.

From these findings it can be concluded that vibration feedback reduces the perceived workload of the teleropation task compared to no feedback. With 22 out of 24 participants demonstrating a lower perceived workload with the addition of vibration feedback compared to no feedback and 18 out of 24 participants demonstrating a lower perceived workload with the addition of vibration feedback compared to visual cues. This is in line with the hypothesis outlined at the beginning of the study.

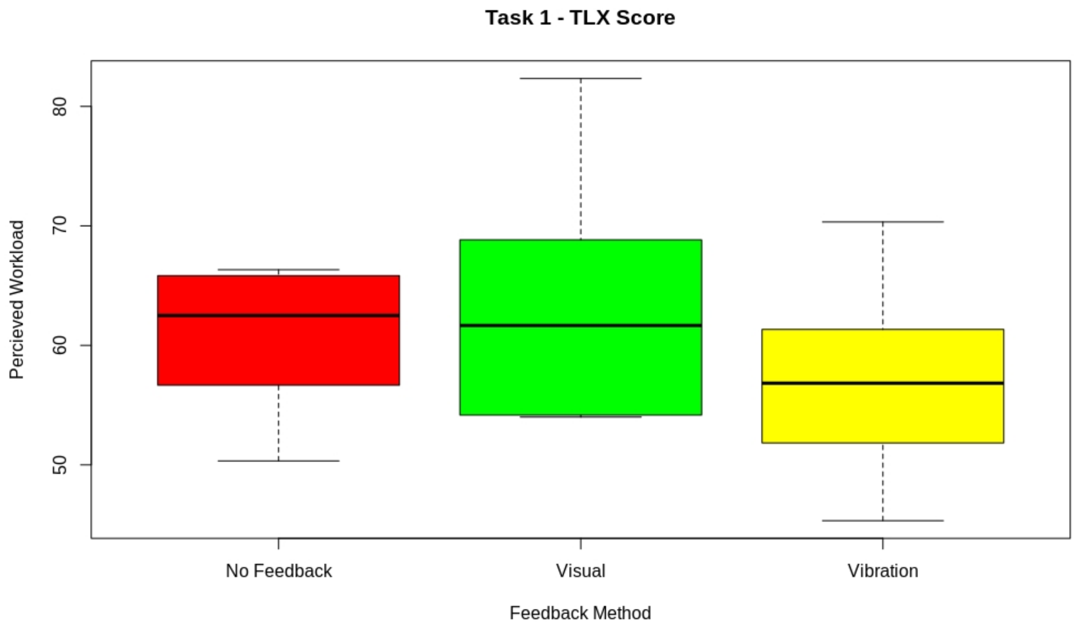


Fig. 10: Task 1 TLX - Feedback methods labelled red (no feedback), green(visual cues) and yellow (vibration feedback). Results showing a reduction in perceived workload with the application of vibration feedback, visual cues showing no consistent results and having a large amount of variation in the data set.

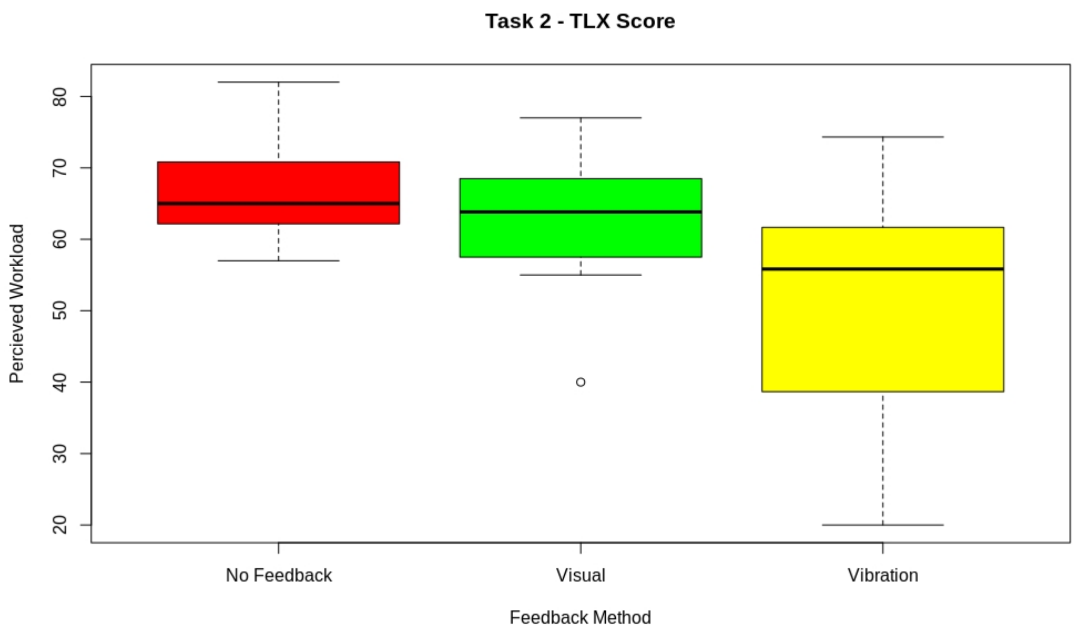


Fig. 11: Task 2 TLX - Feedback methods labelled red (no feedback), green(visual cues) and yellow (vibration feedback). Findings a reduction in perceived workload with the addition of vibration, there is also a large amount of variance in the set itself. Visual feedback demonstration a small reduction in perceived workload but no significant result.

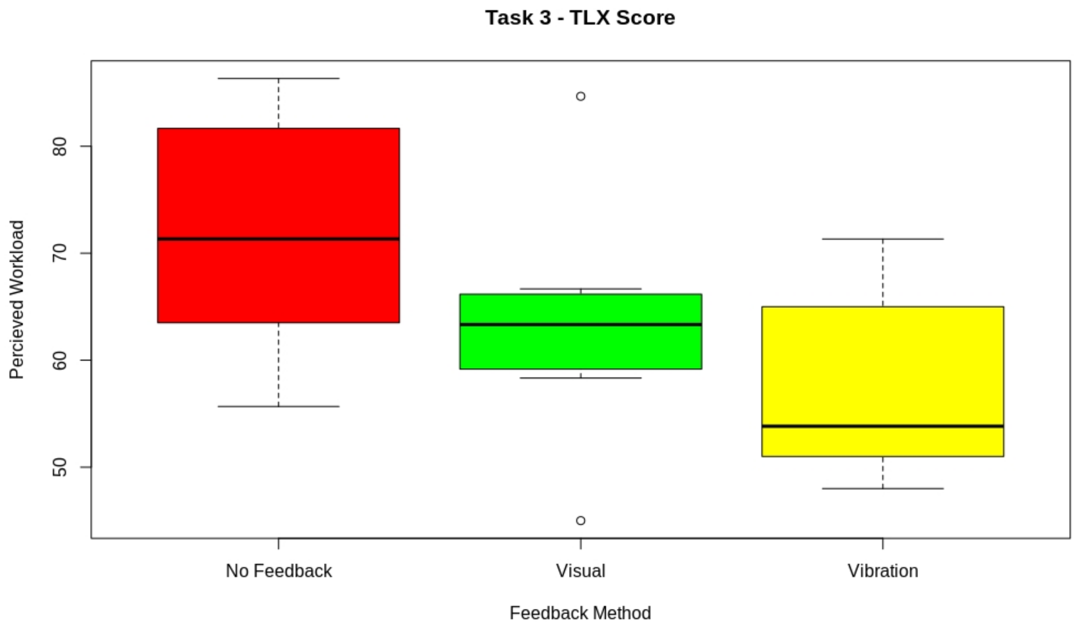


Fig. 12: Task 3 TLX - Feedback methods labelled red (no feedback), green(visual cues) and yellow (vibration feedback). Results show a large reduction in the perceived workload median with the addition of vibration feedback and less so with visual cue, although the variance is reduced within the visual cue condition.

5.3.4 Frustration

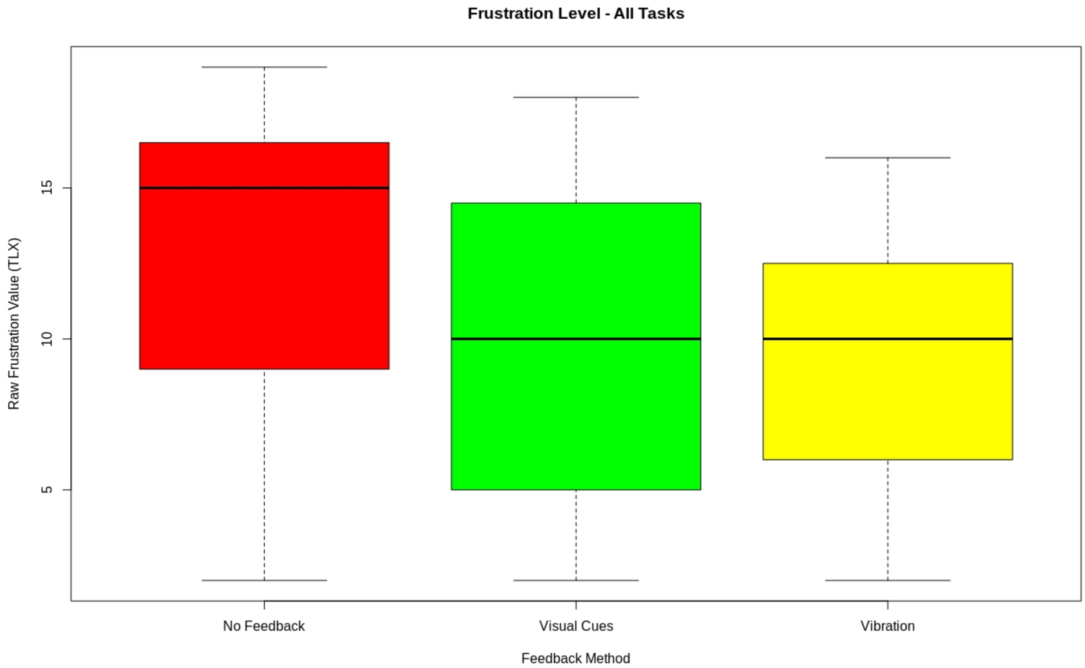


Fig. 13: Frustration Levels

As well as looking at the overall perceived workload of the teleopation task, the study looks at the frustration levels of the teleropation task and the impact the multiple feedback methods have on the metric. This data was collected from the TLX questionnaire and used the raw frustration value provided by each participant on each task.

Fig. 13 shows the results of the frustration values across all three tasks, separated out into the three feedback conditions. As is clear from the boxplot, both visual and vibration feedback have a reduced median compared to the no feedback condition, implying a reduction in overall frustration levels due to the implementation of the feedback methods. Additionally, the vibration condition has a largely reduced variance in data compared to visual feedback, with the data itself being lower values compared to no feedback.

It is possible to implement a binomial test on the individual feedback conditions to look for significance of the results, the p-values being detailed in Table 5.6.

Due to all the p-values being above the 5% significance level the results cannot be considered, regarding a reduction in frustration, conclusive. Although the

Frustration	No./24	P-Value
Visual $<$ No Feedback	15	0.3075
Vibration $<$ No Feedback	16	0.1516
Vibration $<$ Visual Cues	14	0.5413

Table 5.6: Binomial Test Results - Frustration

graph indicates a reduction in frustration levels across the teleoperation tasks, it is not possible to confirm this. This goes against the original hypothesis in relation to frustration.

5.4 Hypothesis Evaluation

This section concludes the hypothesis set out at the beginning of the thesis, to summaries and evaluate if they were correct.

Hypothesis 1 *Participants will complete the task faster on the third (and final) attempt compared to the first attempt*

Confirmed. This has been proven by a binomial test producing p-value's of 0.06391 for task 1, 0.02266 for task 2 and 0.01516 for task 3. Although task 1 is majorial, by having task 2 and task 3 as significant results the conclusion was drawn that the hypothesis is correct and the 3rd attempt is consistently faster than the 1st.

Hypothesis 2 *Both Visual Cues and Vibration Feedback will reduce the overall time of completion across all tasks (compared to No Feedback)*

Not confirmed. The results have shown conclusively that this is not correct with both the graphical representation and T-Test confirming no significant or marginal results. In some cases the feedback systems are measured to have a negative impact on the task (speculation and not considered a significant finding).

Hypothesis 3 *Vibration Feedback will reduce the overall time of completion compared to Visual Cues*

Not confirmed. The vibration feedback did not reduce the completion time compared to visual cues. This was confirmed via a binomial test of the dataset.

Hypothesis 4 *Both Visual Cues and Vibration Feedback will reduce the error rate across all tasks (compared to No Feedback)*

Not confirmed. The bar graphs show a representation of both feedback methods reducing the error rate across all three tasks, however this is not conclusive. Visual cues are the only feedback method with significant results. Due to all three data sets not being gaussian distributed, it is not possible to draw conclusive results.

Hypothesis 5 *Vibration Feedback will reduce the error rate compared to Visual Cues*

Not confirmed. By looking at the bar graphs it is possible to speculate that it was in fact the opposite, with visual cues reducing the error rate consistently over the three tasks compared to vibration feedback. Due to not having normally distributed data sets it is possible to only speculate this theory.

Hypothesis 6 *Visual Cues and Vibration Feedback will have a lower perceived workload irrespective of the task*

Partially confirmed. Vibration feedback consistently reduces the perceived workload across all three tasks with confirmation from a binomial test proving a p-value of 3.588e-05, a very significant result. Visual cues showing a reduction within the boxplot but no significant results presented from the binomial test.

Hypothesis 7 *Vibration Feedback will lower the perceived workload compared to Visual Cues*

Confirmed. Vibration feedback reduced the perceived workload in comparison to visual cues for all three teleoperation tasks. A p-value of 0.02266 confirmed this as a significant result.

Hypothesis 8 *Visual Cues and Vibration Feedback will reduce the frustration level across all tasks*

Not confirmed. Although both feedback methods presented a reduction within the boxplots there was no significant or marginal result found in regards to a binomial test. Visual cues provided a p-value of 0.3075, vibration being 0.1516.

Hypothesis 9 *Vibration Feedback will reduce the frustration level compared to Visual Cues*

Not confirmed. No significant results found for vibration reducing the frustration level across all tasks compared to that of visual cues. Although, by looking at the p-values (from hypothesis 8) it could be implied vibration reduces the frustration level of a task lower than visual cues. However, this cannot be considered a significant finding as it is not near the 5% significance threshold.

5.5 Research Findings

The most important finding within this research study can be considered to be the effects vibration feedback has on reducing the overall perceived workload of a task. By using NASA-TLX it was possible to analyse the individual tasks within the teleoperation study in relation to perceived workload. By implementing this over all 24 participants and across 72 tasks with the related feedback method, it is possible to cover all permutations of the study and in turn gain an understanding of the impact vibration and visual cues have on a teleoperation task as a whole. From this analysis it is possible to confirm that vibration feedback significantly reduces the perceived workload of a teleloperation task, compared to no feedback, and more interestingly, compared to visual cues. Both findings presenting a significant result during analysis.

This finding was hypothesised from the outset and can be considered confirmed within the parameters of this study. Additionally visual cues were also hypothesised to reduce the overall perceived workload of a teleoperation task, however this cannot be confirmed due to the results not showing enough significant evidence. This was not only shown from the recordings using the NASA-TLX but also from comments made by participants within the study. A number of participants commented on how the vibration felt more intuitive and required less concentration than having to focus on the additional visual cue system along with the camera feed. These participant comments can be found within the results section of the appendix.

More in depth analysis was placed on the NASA-TLX data, focusing on the frustration levels during the operation of the teleoperation system, with the raw frustration values being extracted and analysed. Although the graphical representation seems to show a reduction in frustration levels with the addition of both vibration feedback and visual feedback, these results were considered to not be significant and therefore cannot be confirmed. This may be due to a relatively small investigation group and dataset.

Results also show a learning effect present within the teleoperation tasks. Across all tasks within the study it was found that participants were able to complete the tasks faster in their third attempt compared to their first attempt. This finding was investigated on the individual tasks; due to having a large amount of variance in the individual tasks, analysing the overall dataset was not possible. Two out of the three tasks investigated were considered to be significant findings with the final being a marginal, from this it is possible to conclude that there is a learning curve to the teleoperation scenarios and that the original hypothesis relating to this is correct.

Furthermore a sizable finding within the study is that neither the vibration feedback or visual cues have a positive impact on reducing both the error rate and overall completion time of tasks during teleoperation, this rejects the original hypothesis set out. Although this finding is contrary to the hypothesis it is not an isolated case, studies such as (Casqueiro et al., 2016) show similar results within a variation of teleoperation scenarios, providing the summary that the completion time between vibration feedback, stiffness feedback and no feedback was "statistically insignificant". A similar outcome to the results presented within this study, the additional vibration feedback and visual cue systems having no significant impact (positive or negative) on the teleoperation system.

5.6 Limitations

Multiple limitations could be considered within the study, the first of which could be the investigation group itself. Due to the study being a preliminary study limited by time constraints, it was decided that a participant group of 24 was most appropriate (4 full sets of the 6 feedback permutations). This could be seen as not enough of an in depth evaluation and would require further validation to concretely prove the results detailed within this paper. Although this proves as an initial investigation of a novel vibration and visual cue system with some interesting results presented.

There are limitations with the participants that could be used to question the results found. The set of participants is unevenly weighted with regards to gender with 17 male and 7 female. Although this is unlikely to affect the results themselves it could be speculated that an even gender split would be more representative and give a better overview. Furthermore, although the participant set provides an age range of 21 to 62 there is a relatively low mean, being 27.70. A better distribution of ages would allow for a fully representative participant list and could potentially affect the results of the teleoperation tasks and correlating technically competency levels.

The participants were made up of an equal split of people being based at Wheatley Campus, Oxford and external locations. This is not a limitation and allows the geographical location of the participants not to be questioned. If all participants had been based at Wheatley Campus this could be considered biased and a limitation of the study set.

Although the data in relation to participant age, gender, dominant hand, eye conditions, technological competency, experience with teleoperation and knowledge of robotics was collected throughout the study, the questionnaire data was not fully analysed.

The tasks themselves were implemented with a static approach, having limited changing variables between the three tasks, for example non changing table height and distance from base of robot. This was decided due to a large volume of the participants having no prior experience using teleoperation systems, and therefore an attempt to make the tasks as simple as possible and allow for statistically strong results. This could be seen as a limitation as the participants were able to gain a level of familiarity with the remote environment, in turn not wholly relying on the sensory information and feedback systems. By changing to a dynamically changing environment between tasks may have been seen as a better approach to the study. However, the scope of the study did not allow for this.

Although the sensing hardware (FSR and Ultrasonic sensors) implemented within this study functioned well it was not the optimum system for the teleoperation tasks. By implementing a sensory system with a greater level of sensitivity, would potentially allow more accurate results. A system such as the Biotac (*SynTouch Sensor* n.d.) would have not only allowed for an increase in sensory information, but also temperature and slip information to be provided to the operator.

6 Future Work

The results presented in this study open up further opportunities for investigation into sensory feedback methods within teleoperation robotic systems. The first being simply increasing the participant size. Some of the results within the current study were considered not to be significant due to not enough evidence being available to reject the null hypothesis. By increasing the participant size and in turn having a larger number of feedback permutations, future studies could potentially find conclusive results with regards to error rate, time of completion and specifically frustration levels.

Further studies could also look at how the remote environment dynamically changes in between or during the teleoperation tasks themselves; assessing if the feedback systems allow for greater insight into the remote environment compared to the currently implemented static approach. This was considered a limitation of the current study as the participants were able to gain an understanding of the basic environment they were teleoperating in, with speculation that they were less reliant on the feedback systems as they knew the parameters of the remote environment.

There could also be developments by running two studies in parallel, one for non experienced teleoperators, in which the tasks are basic, and one for experienced teleoperators, with more challenging tasks. This would allow for greater analysis into the correlation between how such sensory feedback systems are used within the preliminary stages of learning a teleoperation system and if such sensory feedback systems are not used once an operator becomes experienced.

This study focused on only two feedback systems, visual cues and vibration feedback, which provided a base level comparison between the two main feedback systems used within teleoperation. Further research could be conducted by implementing additional feedback systems such as force feedback to see if such systems provide a reduction in the overall time of completion and error rate whilst reducing the frustration level and perceived workload. For such a study to go ahead, one requirement would be having a more advanced sensing system such as the Biotac by SynTouch (*SynTouch Sensor* n.d.), detailed within the literature review of this thesis.

Some results presented with this study could have been affected by the participants' lack of experience with teleoperation systems. A further study could assess the impact of the sensory feedback method over multiple periods of teleoperation. With participants returning regularly to complete a range of teleoperation tasks. This further research would gain a more in depth analysis of such sensory feedback systems without being affected by the steep learning curve presented within this study. It would be interesting to see results from such a study that analysed the impact of sensory feedback systems over a longer period of time.

7 Conclusion

This dissertation presents the development and implementation of a teleoperation system based on Rethink Robotics' Baxter robot using HTC Vive as the control method. A sensory system is integrated using FSR sensors and ultrasonic depth sensors, with multiple sensory feedback methods (Visual Cues and Vibration Feedback) being developed and integrated.

The development of novel vibration and visual cue systems have been detailed within this paper, providing the operator with sensory feedback information relating to the remote environment being teleoperated. The vibration system developed as a solution to vibration motors within the HTC Vive controllers and instability in the combined tracking solution, caused by drift of the accelerometer and infrared tracking solution. The vibration system along with wireless communication implemented within this paper, demonstrates potential for further development within other teleoperation and robotic applications.

An assessment criteria is developed, outlining a test environment in which participants and a related feedback system can be assessed for error rate, overall task time, perceived workload and frustration level. This study was undertaken with 24 participants from a range of technological competency levels, mixed experience with teleoperation systems and age range of 21 to 62.

The study produces interesting results into the impact of both visual and vibration feedback in a range of tasks based within a static teleoperation environment. This includes a significant reduction of perceived workload across all tasks with the integration of vibration feedback and the presence of a general learning effect of all teleoperation tasks from a participants first and third attempt. Due to results presenting a significant reduction in perceived workload with the addition of vibration feedback, we are able to make the recommendation of vibration feedback for use within tele-operation tasks that naturally require a high level of concentration or prolonged tasks.

Although only partially statically conclusive, the addition of visual cues showed a reduction in the error rate across all three tasks. From this we can recommend the use of visual feedback for tele-operation tasks that require a high level of accuracy.

Future studies should investigate how the resulting reduction in error rate can be translated into advances of time of completion. Furthermore, it is suggested to develop teleoperation scenarios to include a dynamically changing parameter; including height of table and position in relation to the robot base. Along with this, the suggestion has been made to run two parallel studies which incorporate levels of teleoperation experience in an attempt to find correlations to the impact of sensory feedback methods. Additional, study developments in relation to increased accuracy of sensor technology are also advised.

It is key to make clear that this paper serves as a preliminary study investigating the effects of vibration feedback and visual cues within the parameters of a simple teleoperation task, with significant results found in relation to perceived workload within teleoperation and learning effects. Relating research studies finding similar results across vibration feedback, stiffness feedback and no feedback being "statistically insignificant" in relation to completion time. The study also investigates whether the addition of vibration feedback and visual cues reduce the frustration levels of a teloperation task, with a result seeming to be present within the graphical representations, but no significant findings following further analysis.

Bibliography

Alex, Matt Miller (n.d.). "Evaluating the Effects of Haptic and Visual Feedback on the Teleoperation of Remote Robots". In: () (cit. on p. 16).

Arian, Morelle S et al. (2014). "Using the BioTac as a tumor localization tool". In: *2014 IEEE Haptics Symposium (HAPTICS)*. IEEE, pp. 443–448 (cit. on p. 11).

Brown, Matt (July 2016). *The technology behind HTC Vive controller*. URL: `https://www.vrheads.com/exposing-magic-behind-htc-vive-controller` (cit. on p. 15).

Casqueiro, André et al. (2016). "Improving teleoperation with vibration force feedback and anti-collision methods". In: *Robot 2015: Second Iberian Robotics Conference*. Springer, pp. 269–281 (cit. on p. 73).

Chopra, Nikhil et al. (2004). "On position tracking in bilateral teleoperation". In: *Proceedings of the 2004 American Control Conference*. Vol. 6. IEEE, pp. 5244–5249 (cit. on p. 14).

D'Souza, Aaron, Sethu Vijayakumar, and Stefan Schaal (2001). "Learning inverse kinematics". In: *Proceedings 2001 IEEE/RSJ International Conference on Intelligent Robots and Systems. Expanding the Societal Role of Robotics in the the Next Millennium (Cat. No. 01CH37180)*. Vol. 1. IEEE, pp. 298–303 (cit. on p. 24).

Dahiya, Ravinder S, Giorgio Metta, et al. (2009). "Tactile sensing—from humans to humanoids". In: *IEEE transactions on robotics* 26.1, pp. 1–20 (cit. on p. 8).

Dahiya, Ravinder S and Maurizio Valle (2013). "Tactile sensing: definitions and classification". In: *Robotic Tactile Sensing*. Springer, pp. 13–17 (cit. on p. 6).

De Barros, Paulo G, Robert W Lindeman, and Matthew O Ward (2011). "Enhancing robot teleoperator situation awareness and performance using vibro-tactile and graphical feedback". In: *2011 IEEE Symposium on 3D User Interfaces (3DUI)*. IEEE, pp. 47–54 (cit. on p. 12).

Dennerlein, Jack T, Paul A Millman, and Robert D Howe (1997). "Vibrotactile feedback for industrial telemanipulators". In: *Sixth Annual Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, ASME International Mechanical Engineering Congress and Exposition*. Vol. 61, pp. 189–195 (cit. on pp. 2, 12).

Dennerlein, Jack et al. (2000). "Vibrotactile feedback for an underwater telerobot". In: *Robotics and applications; Robotic and manufacturing systems recent results in research, development and applications International symposium; 8th*. Citeseer, pp. 244–249 (cit. on pp. 2, 5).

Du, Guanglong et al. (2012). "Markerless kinect-based hand tracking for robot teleoperation". In: *International Journal of Advanced Robotic Systems* 9.2, p. 36 (cit. on p. 14).

Glove, CyberGrasp (2016). *CyberGlove Systems Inc* (cit. on p. 15).

Goupil, Marc Y et al. (July 2019). *Haptic feedback glove*. US Patent App. 16/235,588 (cit. on p. 1).

Group, NASA Human Performance Research et al. (1987). "Task load index (NASA-TLX) v1. 0 computerised version". In: *NASA Ames Research Centre* (cit. on pp. 16, 50).

Hasser, Christopher J (1995). *Tactile feedback for a force-reflecting haptic display*. Tech. rep. Armstrong Lab Wright-Patterson AFB OH Crew Systems Directorate (cit. on p. 12).

Hew, Calvin (Aug. 2018). *flightlesskite/vive$_t$eleoperation*. URL: https://github.com/flightlesskite/vive_teleoperation (cit. on pp. 21, 22).

Hirche, Sandra and Martin Buss (2012). "Human-oriented control for haptic teleoperation". In: *Proceedings of the IEEE* 100.3, pp. 623–647 (cit. on pp. 5–7).

Hokayem, Peter F and Mark W Spong (2006). "Bilateral teleoperation: An historical survey". In: *Automatica* 42.12, pp. 2035–2057 (cit. on pp. 1, 6).

HTC Vive (Jan. 2020). URL: https://en.wikipedia.org/wiki/HTC_Vive (cit. on p. 15).

Johnson, Bernadette (June 2018). *How Baxter the Robot Works*. URL: https://science.howstuffworks.com/baxter-robot1.htm (cit. on p. 18).

Kappassov, Zhanat, Juan-Antonio Corrales, and Véronique Perdereau (2015). "Tactile sensing in dexterous robot hands". In: *Robotics and Autonomous Systems* 74, pp. 195–220 (cit. on pp. 6, 9).

Kawasetsu, Takumi et al. (2018). "Mexican-hat-like response in a flexible tactile sensor using a magnetorheological elastomer". In: *Sensors* 18.2, p. 587 (cit. on pp. 10, 11).

Liu, Yugang (2019). "Semi-Autonomous Control of Multi-Robot Teams in Urban Search and Rescue Applications". PhD thesis (cit. on p. 1).

Maiolino, P et al. (2015). "Soft dielectrics for capacitive sensing in robot skins: Performance of different elastomer types". In: *Sensors and Actuators A: Physical* 226, pp. 37–47 (cit. on p. 9).

Nagai, Yasufumi et al. (2002). "Audio feedback system for teleoperation experiments on engineering test satellite VII system design and assessment using eye mark recorder for capturing task". In: *IEEE Transactions on Systems, Man,* *and Cybernetics-Part A: Systems and Humans* 32.2, pp. 237–247 (cit. on pp. 2, 13).

Nasa (Feb. 2017). *NASA TLX*. URL: `https://apps.apple.com/us/app/nasa-tlx/id1168110608` (cit. on p. 50).

Okamura, Allison M (2004). "Methods for haptic feedback in teleoperated robot-assisted surgery". In: *Industrial Robot: An International Journal* (cit. on pp. 2, 13, 16).

Okamura, Allison M (2009). "Haptic feedback in robot-assisted minimally invasive surgery". In: *Current opinion in urology* 19.1, p. 102 (cit. on p. 6).

Peratech (2017). "QTC Multi-Touch Sensors". In: (cit. on p. 10).

Pfeiffer, Sam (Mar. 2018). *Vive Teleop Stuff*. URL: `https://github.com/uts-magic-lab/htc_vive_teleop_stuff` (cit. on pp. 21, 32).

Reddivari, Hitesh et al. (2014). "Teleoperation control of Baxter robot using body motion tracking". In: *2014 International conference on multisensor fusion and information integration for intelligent systems (MFI)*. IEEE, pp. 1–6 (cit. on pp. 14, 15, 17).

ROS Wiki (Nov. 2017). URL: `http://wiki.ros.org/rospy` (cit. on p. 19).

ROS Wiki (n.d.). URL: `http://wiki.ros.org/rosserial_arduino/Tutorials/Arduino%20IDE%20Setup` (cit. on p. 31).

Sarakoglou, Ioannis et al. (2016). "HEXOTRAC: A highly under-actuated hand exoskeleton for finger tracking and force feedback". In: *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, pp. 1033–1040 (cit. on p. 12).

ShadowHand (2019). "Tactile Telerobot - Technical Specification". In: (cit. on pp. 9, 11).

SparkFun (2019). "SparkFun VR IMU Breakout - BNO080". In: (cit. on p. 19).

SynTouch Sensor (n.d.). URL: `https://www.syntouchinc.com/technology/` (cit. on pp. 11, 74, 75).

Tawil, Yahya (June 2017). *An Introduction to Robot Operating System (ROS) - Technical Articles*. URL: `https://www.allaboutcircuits.com/technical-articles/an-introduction-to-robot-operating-system-ros/` (cit. on p. 19).

Weber, Paul et al. (2016). "A low-cost sensor glove with vibrotactile feedback and multiple finger joint and hand motion sensing for human-robot interaction". In: *2016 25th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN)*. IEEE, pp. 99–104 (cit. on p. 15).

Wettels, N, J Fishel, and G Loeb (2014). "The Human Hand as an Inspiration for Robot Hand Development". In: *Springer Tracts in Advanced Robotics (STAR) Series. Springer International Publishing*, p. 0912260 (cit. on p. 8).

Whitney, David et al. (2020). “Comparing robot grasping teleoperation across desktop and virtual reality with ROS reality”. In: *Robotics Research*. Springer, pp. 335–350 (cit. on pp. 2, 16).

Yousef, Hanna, Mehdi Boukallel, and Kaspar Althoefer (2011). “Tactile sensing for dexterous in-hand manipulation in robotics—A review”. In: *Sensors and Actuators A: physical* 167.2, pp. 171–187 (cit. on p. 11).

Yussof, Hanafiah et al. (2008). “Determination of object stiffness control parameters in robot manipulation using a prototype optical three-axis tactile sensor”. In: *SENSORS, 2008 IEEE*. IEEE, pp. 992–995 (cit. on p. 10).

Appendix

1 Results Table

Set	Participant No.	Overall Attempt	Task Attempt	Task No.	Feedback Method	Overall Time	Fastest Run	Average Time	Error Rate	TLX Score	Frustration Value	Age	Gender	Dominant Hand	Technologically Competency	Knowledge of Robotics	Previous Teleoperation Experience
1	103	1	1	1	No	20.84			1			22	M	R	70	80	Y
	103	2	2	1	No	53.43			2			-	-	-	-	-	-
	103	3	3	1	No	26.75	20.84	33.67	2	66.33	65	-	-	-	-	-	-
	103	4	1	2	Vibration	43.73			1			-	-	-	-	-	-
	103	5	2	2	Vibration	30.12			0			-	-	-	-	-	-
	103	6	3	2	Vibration	34.6	30.12	36.15	1	62.67	60	-	-	-	-	-	-
	103	7	1	3	Visual	19.9			0			-	-	-	-	-	-
	103	8	2	3	Visual	20.74			0			-	-	-	-	-	-
	103	9	3	3	Visual	16.77	16.77	19.14	0	66.67	60	-	-	-	-	-	-
2	316	1	1	1	Visual	49.89			0			25	M	R	35	5	N
	316	2	2	1	Visual	51.1			1			-	-	-	-	-	-
	316	3	3	1	Visual	31.17	31.17	44.05	0	58.33	25	-	-	-	-	-	-

	316	4	1	2	No	62.75			1			-	-	-	-	-	-
	316	5	2	2	No	77.53			2			-	-	-	-	-	-
	316	6	3	2	No	89.66	62.75	76.65	3	71.67	90	-	-	-	-	-	-
	316	7	1	3	Vibration	49.91			0			-	-	-	-	-	-
	316	8	2	3	Vibration	45.12			0			-	-	-	-	-	-
	316	9	3	3	Vibration	32.08	32.08	42.37	1	71.33	70	-	-	-	-	-	-
3	216	1	1	1	Vibration	110.98			0			24	F	L	45	15	”N
	216	2	2	1	Vibration	56.73			0			-	-	-	-	-	-
	216	3	3	1	Vibration	70.17	56.73	79.29	1	70.33	40	-	-	-	-	-	-
	216	4	1	2	Visual	142.07			1			-	-	-	-	-	-
	216	5	2	2	Visual	77.06			1			-	-	-	-	-	-
	216	6	3	2	Visual	76.07	76.07	98.4	0	77	60	-	-	-	-	-	-
	216	8	2	3	No	56.66			1			-	-	-	-	-	-
	216	9	3	3	No	66.07	23.18	48.64	2	84.67	85	-	-	-	-	-	-
4	264	1	1	1	No	81.62			2			21	F	R	50	15	”N
	264	2	2	1	No	129.59			4			-	-	-	-	-	-
	264	3	3	1	No	62.83	62.83	91.35	0	63	75	-	-	-	-	-	-
	264	4	1	2	Visual	156.65			1			-	-	-	-	-	-
	264	5	2	2	Visual	109.33			1			-	-	-	-	-	-
	264	6	3	2	Visual	84.04	84.04	116.67	2	72.67	50	-	-	-	-	-	-
	264	7	1	3	Vibration	36.54			1			-	-	-	-	-	-
	264	8	2	3	Vibration	27.14			0			-	-	-	-	-	-
	264	9	3	3	Vibration	42.92	27.14	35.53	1	62.33	30	-	-	-	-	-	-
5	372	1	1	1	Visual	100.09			1			22	M	R	40	10	N
	372	3	3	1	Visual	61.79	61.79	83.91	1	54.33	25	-	-	-	-	-	-
	372	4	1	2	Vibration	99.35			1			-	-	-	-	-	-
	372	5	2	2	Vibration	87.59			1			-	-	-	-	-	-

	372	6	3	2	Vibration	73.26	73.26	86.73	0	34.33	30	-	-	-	-	-	-
	372	7	1	3	No	34.7			1			-	-	-	-	-	-
	372	8	2	3	No	86.14			2			-	-	-	-	-	-
	372	9	3	3	No	38.49	34.7	53.11	0	55.67	50	-	-	-	-	-	-
6	193	1	1	1	Vibration	63.66			3			22	M	R	60	10	N
	193	2	2	1	Vibration	37.02			0			-	-	-	-	-	-
	193	3	3	1	Vibration	42.53	37.02	47.74	3	56.67	50	-	-	-	-	-	-
	193	4	1	2	No	119.94			4			-	-	-	-	-	-
	193	5	2	2	No	58.74			1			-	-	-	-	-	-
	193	6	3	2	No	81.94	58.74	86.87	3	61.33	30	-	-	-	-	-	-
	193	7	1	3	Visual	38.53			1			-	-	-	-	-	-
	193	8	2	3	Visual	25.14			1			-	-	-	-	-	-
	193	9	3	3	Visual	30.63	25.14	31.43	0	62	40	-	-	-	-	-	-
1	189	1	1	1	No	159.32			4			30	F	R	60	45	N
	189	2	2	1	No	70.87			1			-	-	-	-	-	-
	189	3	3	1	No	105.84	70.87	112.01	4	66	70	-	-	-	-	-	-
	189	4	1	2	Vibration	222.07			3			-	-	-	-	-	-
	189	5	2	2	Vibration	172.46			5			-	-	-	-	-	-
	189	6	3	2	Vibration	302.6	172.46	232.38	4	55.67	70	-	-	-	-	-	-
	189	7	1	3	Visual	20.41			0			-	-	-	-	-	-
	189	8	2	3	Visual	86.14			2			-	-	-	-	-	-
	189	9	3	3	Visual	15.9	20.41	40.82	0	84.67	85	-	-	-	-	-	-
2	56	1	1	1	Visual	188.1			0			29	F	R	50	20	N
	56	2	2	1	Visual	171.8			4			-	-	-	-	-	-
	56	3	3	1	Visual	131.17	131.17	163.69	2	82.33	75	-	-	-	-	-	-
	56	4	1	2	No	133.19			3			-	-	-	-	-	-
	56	5	2	2	No	91.46			1			-	-	-	-	-	-

	56	6	3	2	No	122.08	91.46	115.58	1	63	65	-	-	-	-	-	-
	56	7	1	3	Vibration	99.08			3			-	-	-	-	-	-
	56	8	2	3	Vibration	39.42			0			-	-	-	-	-	-
	56	9	3	3	Vibration	34.79	34.79	57.76	1	48	30	-	-	-	-	-	-
3	455	1	1	1	Vibration	73.37			2			22	M	R	85	90	Y
	455	2	2	1	Vibration	50.17			1			-	-	-	-	-	-
	455	3	3	1	Vibration	67.55	50.17	63.7	4	45.33	35	-	-	-	-	-	-
	455	4	1	2	Visual	77.34			2			-	-	-	-	-	-
	455	5	2	2	Visual	71.19			3			-	-	-	-	-	-
	455	6	3	2	Visual	73.85	71.19	74.13	0	60	55	-	-	-	-	-	-
	455	7	1	3	No	70.2			1			-	-	-	-	-	-
	455	9	3	3	No	34.32	28.98	44.5	0	59.67	75	-	-	-	-	-	-
4	197	1	1	1	No	98.44			6			24	F	L	60	10	N
	197	2	2	1	No	63.83			3			-	-	-	-	-	-
	197	3	3	1	No	31.48	31.48	64.58	1	54.33	65	-	-	-	-	-	-
	197	4	1	2	Visual	129.25			4			-	-	-	-	-	-
	197	5	2	2	Visual	86.4			4			-	-	-	-	-	-
	197	6	3	2	Visual	64.33	64.33	93.33	1	63.67	70	-	-	-	-	-	-
	197	7	1	3	Vibration	27.57			1			-	-	-	-	-	-
	197	8	2	3	Vibration	48.59			1			-	-	-	-	-	-
	197	9	3	3	Vibration	86.4	48.59	54.19	4	51	55	-	-	-	-	-	-
5	430	1	1	1	Visual	71.59			1			61	F	R	45	35	N
	430	2	2	1	Visual	140.09			2			-	-	-	-	-	-
	430	3	3	1	Visual	84.23	71.59	98.64	3	72.33	20	-	-	-	-	-	-
	430	4	1	2	Vibration	127.74			1			-	-	-	-	-	-
	430	5	2	2	Vibration	274.4			8			-	-	-	-	-	-
	430	6	3	2	Vibration	132.33	127.74	178.16	2	74.33	10	-	-	-	-	-	-

	430	7	1	3	No	87.26			1			-	-	-	-	-	-
	430	8	2	3	No	40.84			1			-	-	-	-	-	-
	430	9	3	3	No	46.84	40.84	58.31	1	86.33	10	-	-	-	-	-	-
	20	2	2	1	Vibration	102.16			4			-	-	-	-	-	-
	20	3	3	1	Vibration	100.07	90.61	97.61	3	62.67	50	-	-	-	-	-	-
	20	4	1	2	No	102.75			3			-	-	-	-	-	-
	20	5	2	2	No	124.69			3			-	-	-	-	-	-
	20	6	3	2	No	105.81	102.75	111.08	2	57	25	-	-	-	-	-	-
	20	7	1	3	Visual	34.28			1			-	-	-	-	-	-
	20	8	2	3	Visual	38.44			2			-	-	-	-	-	-
	20	9	3	3	Visual	29.18	29.18	33.97	0	60	40	-	-	-	-	-	-
1	168	1	1	1	No	102.44			1			26	M	R	95	55	N
	168	2	2	1	No	72.9			2			-	-	-	-	-	-
	168	3	3	1	No	62.19	62.19	79.18	1	65.67	70	-	-	-	-	-	-
	168	5	2	2	Vibration	122.79			0			-	-	-	-	-	-
	168	6	3	2	Vibration	107.03	107.03	114.81	1	20	5	-	-	-	-	-	-
	168	7	1	3	Visual	174.11			1			-	-	-	-	-	-
	168	8	2	3	Visual	79.38			0			-	-	-	-	-	-
	168	9	3	3	Visual	68.97	68.97	107.49	0	65.67	70	-	-	-	-	-	-
2	517	1	1	1	Visual	84.74			1			23	M	R	95	65	N
	517	2	2	1	Visual	66.69			3			-	-	-	-	-	-
	517	3	3	1	Visual	57.53	57.53	69.65	1	65.33	65	-	-	-	-	-	-
	517	4	1	2	No	90.89			0			-	-	-	-	-	-
	517	5	2	2	No	89.22			2			-	-	-	-	-	-
	517	6	3	2	No	131.43	89.22	103.85	1	82	80	-	-	-	-	-	-
	517	7	1	3	Vibration	27.21			0			-	-	-	-	-	-
	517	8	2	3	Vibration	24.23			0			-	-	-	-	-	-

	517	9	3	3	Vibration	30.38	24.23	27.27	0	51	35	-	-	-	-	-	-
3	157	1	1	1	Vibration	36.36			1			23	M	R	95	75	Y
	157	2	2	1	Vibration	62.2			5			-	-	-	-	-	-
	157	3	3	1	Vibration	40.97	36.36	46.51	1	52	5	-	-	-	-	-	-
	157	4	1	2	Visual	120.73			1			-	-	-	-	-	-
	157	5	2	2	Visual	84.95			2			-	-	-	-	-	-
	157	6	3	2	Visual	54.8	54.8	86.83	1	64	10	-	-	-	-	-	-
	157	7	1	3	No	29.62			0			-	-	-	-	-	-
	157	8	2	3	No	17.64			0			-	-	-	-	-	-
	157	9	3	3	No	16.92	16.92	21.39	0	68	20	-	-	-	-	-	-
4	10	1	1	1	No	81.5			2			21	M	L	65	5	N
	10	2	2	1	No	107.72			4			-	-	-	-	-	-
	10	3	3	1	No	66.62	66.62	85.28	0	62	75	-	-	-	-	-	-
	10	4	1	2	Visual	89.66			2			-	-	-	-	-	-
	10	5	2	2	Visual	56.91			1			-	-	-	-	-	-
	10	6	3	2	Visual	69.12	56.91	71.9	2	55	70	-	-	-	-	-	-
	10	7	1	3	Vibration	29.45			0			-	-	-	-	-	-
	10	8	2	3	Vibration	21.06			1			-	-	-	-	-	-
	10	9	3	3	Vibration	23.63	21.06	24.71	0	53.33	65	-	-	-	-	-	-
	53	2	2	1	Visual	49.03			1			-	-	-	-	-	-
	53	3	3	1	Visual	41.6	41.6	47.15	1	54	45	-	-	-	-	-	-
	53	4	1	2	Vibration	75.9			1			-	-	-	-	-	-
	53	6	3	2	Vibration	46.65	46.65	60.18	1	43	50	-	-	-	-	-	-
	53	7	1	3	No	33.66			2			-	-	-	-	-	-
	53	8	2	3	No	64.99			2			-	-	-	-	-	-
	53	9	3	3	No	51.49	51.49	50.05	3	74.67	80	-	-	-	-	-	-
6	322	1	1	1	Vibration	76.12			2			25	F	R	55	10	N

	322	2	2	1	Vibration	52.03			1			-	-	-	-	-	-
	322	3	3	1	Vibration	35.69	35.69	54.61	1	57	20	-	-	-	-	-	-
	322	4	1	2	No	98.14			5			-	-	-	-	-	-
	322	5	2	2	No	79.03			4			-	-	-	-	-	-
	322	6	3	2	No	132.05	79.03	103.07	5	64.33	75	-	-	-	-	-	-
	322	7	1	3	Visual	30.94			0			-	-	-	-	-	-
	322	8	2	3	Visual	114.14			3			-	-	-	-	-	-
	322	9	3	3	Visual	28.58	30.94	57.89	0	45	15	-	-	-	-	-	-
1	199	1	1	1	No	56.5			2			62	M	R	65	70	N
	199	2	2	1	No	63.03			1			-	-	-	-	-	-
	199	3	3	1	No	57.61	57.61	59.05	2	50.33	35	-	-	-	-	-	-
	199	4	1	2	Vibration	110.2			4			-	-	-	-	-	-
	199	5	2	2	Vibration	120.58			1			-	-	-	-	-	-
	199	6	3	2	Vibration	101.32	101.32	110.7	1	56	55	-	-	-	-	-	-
	199	7	1	3	Visual	83.63			2			-	-	-	-	-	-
	199	8	2	3	Visual	32.55			0			-	-	-	-	-	-
	199	9	3	3	Visual	30.86	30.86	49.01	1	58.33	60	-	-	-	-	-	-
2	172	1	1	1	Visual	48.05			1			27	M	R	75	55	Y
	172	2	2	1	Visual	81.9			3			-	-	-	-	-	-
	172	3	3	1	Visual	74.86	48.05	68.27	4	54	30	-	-	-	-	-	-
	172	4	1	2	No	69.83			1			-	-	-	-	-	-
	172	5	2	2	No	74.36			2			-	-	-	-	-	-
	172	6	3	2	No	67.24	67.24	70.48	3	70	60	-	-	-	-	-	-
	172	7	1	3	Vibration	42.17			1			-	-	-	-	-	-
	172	8	2	3	Vibration	34.05			0			-	-	-	-	-	-
	172	9	3	3	Vibration	36.59	34.05	37.6	1	67.67	65	-	-	-	-	-	-
3	108	1	1	1	Vibration	62.05			1			29	M	R	65	65	N

	108	2	2	1	Vibration	109.99			3			-	-	-	-	-	-
	108	3	3	1	Vibration	84.22	62.05	85.42	0	60	15	-	-	-	-	-	-
	108	4	1	2	Visual	207.83			1			-	-	-	-	-	-
	108	5	2	2	Visual	175.33			2			-	-	-	-	-	-
	108	6	3	2	Visual	163.49	163.49	182.22	2	64.33	20	-	-	-	-	-	-
	108	7	1	3	No	379.04			2			-	-	-	-	-	-
	108	8	2	3	No	57.1			0			-	-	-	-	-	-
	108	9	3	3	No	83.49	57.1	173.21	0	78.67	75	-	-	-	-	-	-
4	299	1	1	1	No	130.1			6			26	M	R	75	15	N
	299	2	2	1	No	41.18			2			-	-	-	-	-	-
	299	3	3	1	No	73.55	41.18	81.61	3	59	15	-	-	-	-	-	-
	299	4	1	2	Visual	93.83			2			-	-	-	-	-	-
	299	5	2	2	Visual	43.89			1			-	-	-	-	-	-
	299	6	3	2	Visual	82.13	43.89	73.28	1	40	15	-	-	-	-	-	-
	299	7	1	3	Vibration	55.92			0			-	-	-	-	-	-
	299	8	2	3	Vibration	32.25			0			-	-	-	-	-	-
	299	9	3	3	Vibration	65.38	32.25	51.18	2	54.33	20	-	-	-	-	-	-
5	268	1	1	1	Visual	81.42			2			26	M	R	70	20	N
	268	2	2	1	Visual	38.99			0			-	-	-	-	-	-
	268	3	3	1	Visual	27.04	27.04	49.15	0	65	80	-	-	-	-	-	-
	268	4	1	2	Vibration	60.9			2			-	-	-	-	-	-
	268	5	2	2	Vibration	55.52			1			-	-	-	-	-	-
	268	6	3	2	Vibration	49.58	49.58	55.33	2	60.67	75	-	-	-	-	-	-
	268	7	1	3	No	78.6			1			-	-	-	-	-	-
	268	8	2	3	No	46.71			1			-	-	-	-	-	-
	268	9	3	3	No	35.2	35.2	53.5	3	67.33	90	-	-	-	-	-	-
6	505	1	1	1	Vibration	163.5			4			27	M	L	85	50	N

	505	2	2	1	Vibration	100.48			2			-	-	-	-	-	-
	505	3	3	1	Vibration	87.56	87.56	117.18	4	51.67	25	-	-	-	-	-	-
	505	4	1	2	No	130.86			2			-	-	-	-	-	-
	505	6	3	2	No	59.52	59.52	86.41	1	65.67	80	-	-	-	-	-	-
	505	7	1	3	Visual	40.18			1			-	-	-	-	-	-
	505	9	3	3	Visual	61.5	40.18	58.38	1	64.67	35	-	-	-	-	-	-

2 Participant Information

2.1 Task Information Sheet

An experimental investigation of tactile sensory feedback methods within tele-operation robotic system

You are being invited to take part in a research study. Before you decide whether or not to take part, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully.

What is the purpose of the study?

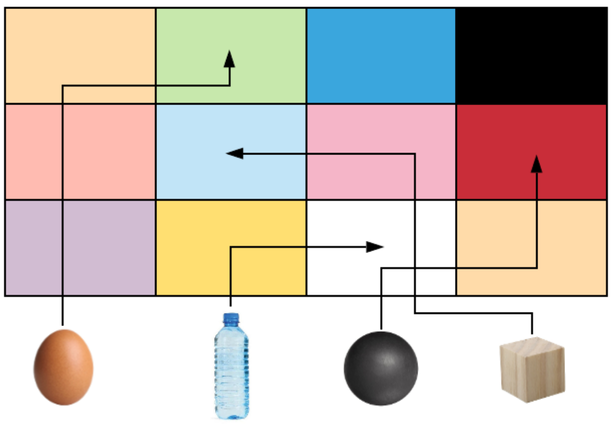
This study aims to assess the influence of tactile sensory feedback methods in tele-operation robotic systems. The results recorded within this study will be used to publish research material to outline the effect of a selected number of feedback methods in real world tele-operation tasks.

During the tele-operation task, you will be asked to control a robot to pick up objects remotely. 3 minutes will be allocated to gain familiarity with the robot and control interface, there will be objects on the table for you to manipulate during this period. Please make the most of this time.

You will complete a set of tasks 3 times, moving individual items into labelled areas on the table. You will operate the robot with no feedback, visual cues and vibration feedback, you will be notified before undertaking the task which feedback method you will be using. The system will be monitored throughout including time. Please aim to complete every pick and place task as quick as you can, whilst still putting the object in the area indicated. If you drop any objects they will be reset, with a maximum time of 2 minutes for each task.

If you would like a demonstration of the system please ask now.

Objects :



Following Instructions for object placement

Why have I been invited to participate?

This study aims to record the results of 25-30 participants from a variety of backgrounds with no intentional biases towards race, age or gender. By consenting to be involved you agree to take part in the study, please notify Thomas Baker with your study ID number if you would no longer like to take part in the study. This can be at any time before, during or after the study has been carried out.

Do I have to take part?

It is completely your choice if you would like to take part in the research study. Limited personal data is needed for this study although your age, gender, technical ability and video footage are recorded. Please look at the privacy notice if you would like to know what information is being stored. All data is anonymously collected and stored on a secure encrypted database remotely.

What will happen to me if I take part?

You will be asked to perform the task explained in the first section of this document, your times will be recorded throughout. As previously stated video footage will be taken throughout the study. This data will be stored in an encrypted folder from which it will be analysed to aid the conclusion for the overall study.

Following completion of the task using each feedback method you will be asked to fill out a NASA-TLX, a widely-used questionnaire tool.

Recorded video may also be used in presentations or demonstrations about the project. As a volunteer, you have the ability to withdraw your consent for both use of video and use of your results at any point following the experiment.

What are the possible disadvantages and risks of taking part?

You may feel some forms of stress and discomfort whilst undertaking the task. This is limited but may affect different participants uniquely. If at any point you would like to stop the task please use the stop button provided or make Thomas Baker aware. This task is deliberately difficult and can be stopped at any time if required.

The greatest disadvantage of being part of this study is time, to undertake the task multiple times with different feedback methods is predicted to take around half an hour. Please allow 45 minutes including the assessment section of the study. Please make sure you can committee this time before signing the consent form.

What are the possible benefits of taking part?

As a participant of this study you will be supporting the growth of an ever increasing research field. Tele-robotics has a huge potential and such studies play a part towards pushing this technology forward and diversifying the applications.

Will what I say in this study be kept confidential?

All data will be stored anonymously with a unique ID for each participant. Personal details (age and gender) of each participant will be stored remotely on an encrypted database and only accessed if a participant would no longer like to be included in the study.

This anonymous ID number will then be used in conjunction with the test data, all test data will be stored in a secure location. Furthermore. once you have completed the task your questionnaire will be photocopied and stored in this location.

All videos taken as part of the study will be censored live using facial detection technology, this will minimize the biometric data stored within the system (biometric data being faces).

Any test results will be published in the form of a dissertation, oral presentations and poster publications at conferences.

What will happen to the results of the research study?

The results from this research will be presented within a thesis for Thomas Baker's MSc By Research. The intent is to publish this research material at conferences, online and will be available to the general public. Specific data sets and participant identifies will not be publicly available at any point although anonymous ID numbers and related performance data will be available within the appendices of the final thesis.

Who is organising and funding the research?

This research has been organised and funded by master's student Thomas Baker with the supervision of Dr Mathias Rolf and Dr Tjeerd Olde Scheper for the department of Technology, Design and Environment at Oxford Brookes University.

Who has reviewed the study?

This research has been approved by the University Research Ethics Committee, Oxford Brookes University.

Contact for Further Information

For any further information about the study the emails for the researchers on this project are listed below:
Thomas Baker:
18098352@brookes.ac.uk

Matthias Rolf:
mrolf@brookes.ac.uk

Tjeerd Old Scheper
tvolde-scheper@brookes.ac.uk

If you have any concerns about the way in which the study has been conducted contact the Chair of the University Research Ethics Committee on ethics@brookes.ac.uk.

Thank you for taking time to read this information, please feel free to volunteer for this experiment if it interests you.

Thank you

I would like to take this opportunity to thank you for taking the time to be part of this study.

Version Number
Version 4

2.2 GDPR & Data Storage Information

OXFORD BROOKES UNIVERSITY

Privacy notice for research participants

This privacy notice provides information on how Oxford Brookes University collects and uses your personal information when you take part in one of our research projects. Please refer to the research participant information sheet for further details about the study and what information will be collected about you and how it will be used.

Oxford Brookes University (OBU) will usually be the Data Controller of any data that you supply for this research. This means that we are responsible for looking after your information and using it properly. The exception to this is joint research projects where you would be informed on the participant information sheet as to the other partner institution or institutions. This means that they will make the decisions on how your data is used and for what reasons. You can contact the University's Information Management Team on 01865 485420 or email info.sec@brookes.ac.uk.

Why do we need your data?
This study aims to assess the influence of tactile sensory feedback in tele-operation robotic systems. The results recorded within this study will be used to publish research material to outline the effect of multiple feedback methods in real world tele-operation tasks.

OBUs legal basis for collecting this data is:

- You are consenting to providing it to us; and / or,
- Processing is necessary for the performance of a task in the public interest such as research

If the university asks you for sensitive data such as; racial or ethnic origin, political opinions, religious or philosophical beliefs, trade-union membership, data concerning health or sexual life, genetic/biometric data or criminal records OBU will use these data because:

- You have given OBU explicit consent to do so; and / or
- Processing is necessary for scientific or research in the public interest.

What type of data will Oxford Brookes University use?
An amount of personal data will be collected, including name, age, gender and any visual imparments. This data will be linked to a unique ID number which will hold information regarding the tasks undertaken within the study including performance times. Video footage will also be taken of all participants although will be censored if requested.

All data recorded within this study will be stored within a secure databse.

Who will OBU share your data with?
The study uses an application developed by NASA to measure the workload of a task, all data being stored on their server. The NASA TLX has been designed to ensure the privacy of research participant data. The NASA TLX application anonymizes all results and does not send any personal identifiable information to any data servers.

Will OBU transfer my data outside of the UK?
No

What rights do I have regarding my data that OBU holds?

- You have the right to be informed about what data will be collected and how this will be used
- You have the right of access to your data
- You have the right to correct data if it is wrong
- You have the right to ask for your data to be deleted
- You have the right to restrict use of the data we hold about you
- You have the right to data portability

- You have the right to object to the university using your data
- You have rights in relation to using your data in automated decision making and profiling.

Where did OBU source my data from?
All data will come from participants within this study. Personal data will be recorded within the initial consent form and questionnaire at the beginning of the study.

Are there any consequences of not providing the requested data?
There are no consequences of not providing data for this research. It is purely voluntary.

Will there be any automated decision making using my data?
There will be no use of automated decision making in scope of UK Data Protection and Privacy legislation.

How long will OBU keep your data?
In line with Oxford Brookes policies data generated in the course of research must be kept securely in paper or electronic form for a period of time in accordance with the research funder or University policy

Who can I contact if I have concerns?
In the event of any questions about the research study, please contact the researchers in the first instance (contact details in the study participant information sheet). If you have any concerns about the way in which the study has been conducted, contact the Chair of the University Research Ethics Committee at ethics@brookes.ac.uk. For further details about information security contact the Data Protection Officer at: brookesdpo@brookes.ac.uk or the Information Management team on info.sec@brookes.ac.uk

2.3 Participant Consent Form

Study ID Number :

OXFORD BROOKES UNIVERSITY

CONSENT FORM

An experimental investigation of tactile sensory feedback methods within teleoperation robotic system

Researcher	**Supervisor**
Thomas Baker - MSc Student	Dr Matthias Rolf
18098352@brookes.ac.uk	mrolf@brookes.ac.uk

Please initial box

1. I confirm that I have read and understand the information sheet for the above study and have had the opportunity to ask questions. ☐
2. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving reason. ☐
3. I agree to take part in the above study. ☐

Please initial box

	Yes	No
4. I agree to the tele-operation task being video recorded	☐	☐
4. I am happy for videos to be uncensored	☐	☐
5. I agree to the censored videos being publicised	☐	☐
6. I agree to the use of anonymised quotes & data sets in publications	☐	☐
7. I agree that an anonymised data set, gathered for this study may be stored in a specialist data centre/repository relevant to this subject area for future research	☐	☐

Name of Participant　　　Date　　　Signature

Name of Researcher　　　Date　　　Signature

Study Questionnaire

Study ID Number :

Study Questionnaire

The questions asked within this questionnaire are completely confidential, all data recorded is to ensure the study data is unbiased. Please complete this form carefully making sure all answers are accurate.

What is your age?

What is your gender?

Do you have any visual impairments?

Do you have any medical conditions that affect hand eye coordination?

What is your dominant hand?

How technologically competent are you?

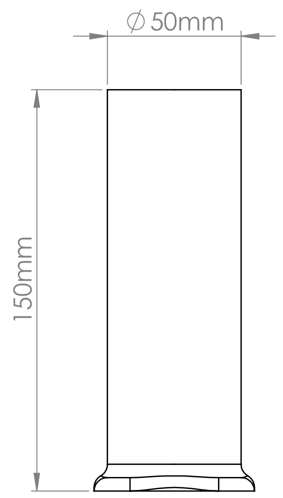
None **Expert**

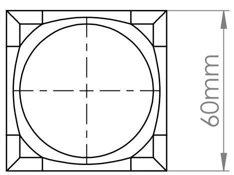
How much knowledge or understanding do you have of robotics and robotic systems?

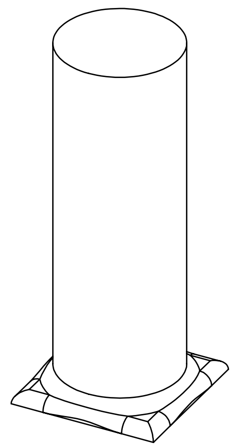
None **Expert**

Have you ever used a tele-operation robotic system before?

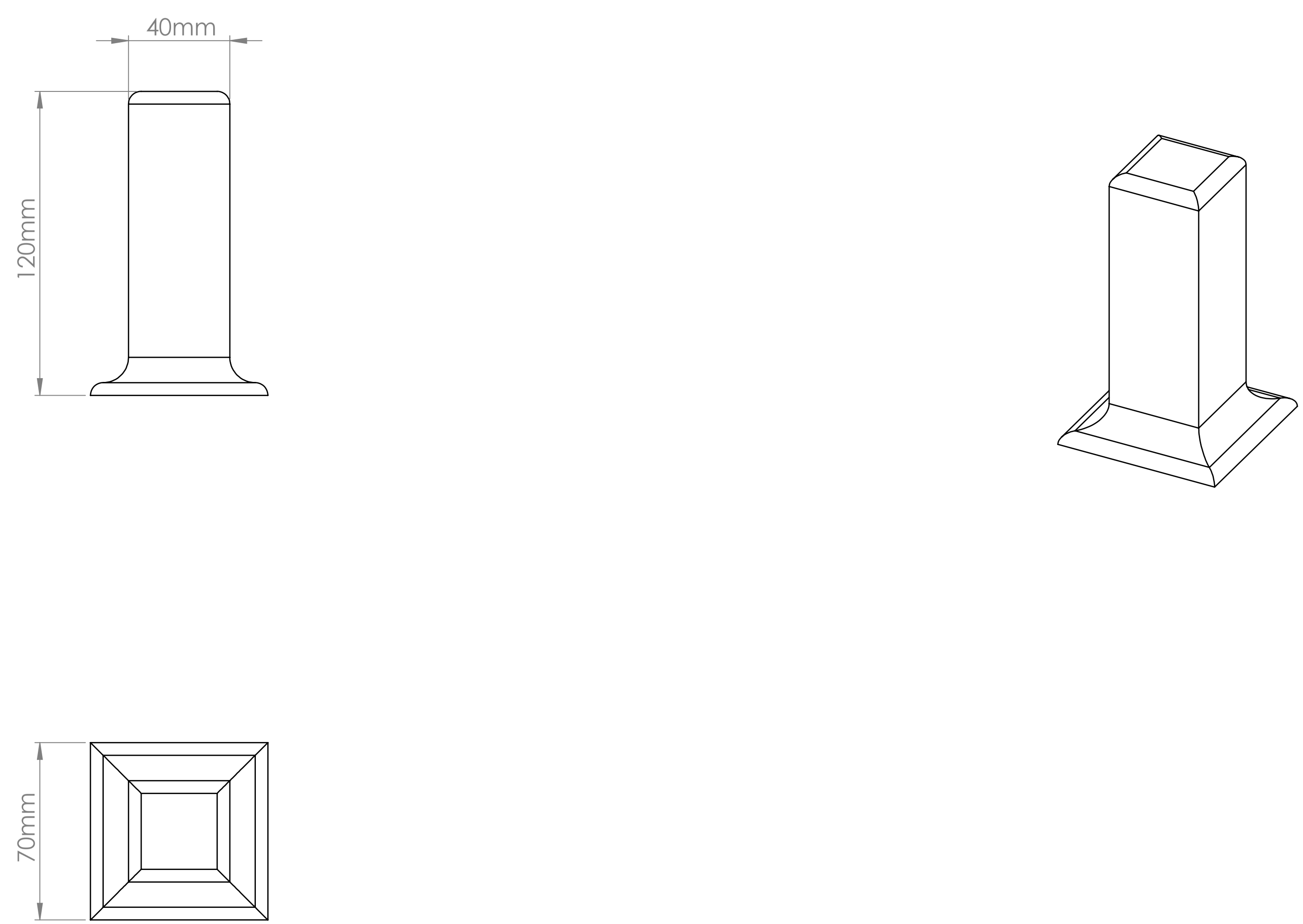
3 Study Object Dimensions







UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS TOLERANCE: ±0.5 mm	NOTES: 3D PRINTED OBJECT MATERIAL - PLA	DO NOT SCALE DRAWING	REVISION A
DRAWN — NAME: Thomas Baker — DATE: 03 Feb 2020		TITLE: Practice Object 1	SHEET 1 OF 1



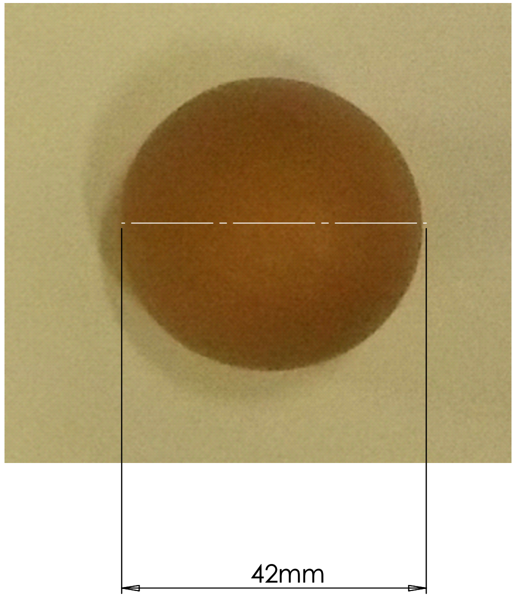
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS TOLERANCE: ±0.5 mm	NOTES: 3D PRINTED OBJECT MATERIAL - PLA	DO NOT SCALE DRAWING	REVISION A
		TITLE: Practice Object 2	
DRAWN — NAME: Thomas Baker — DATE: 03 Feb 2020			SHEET 1 OF 1

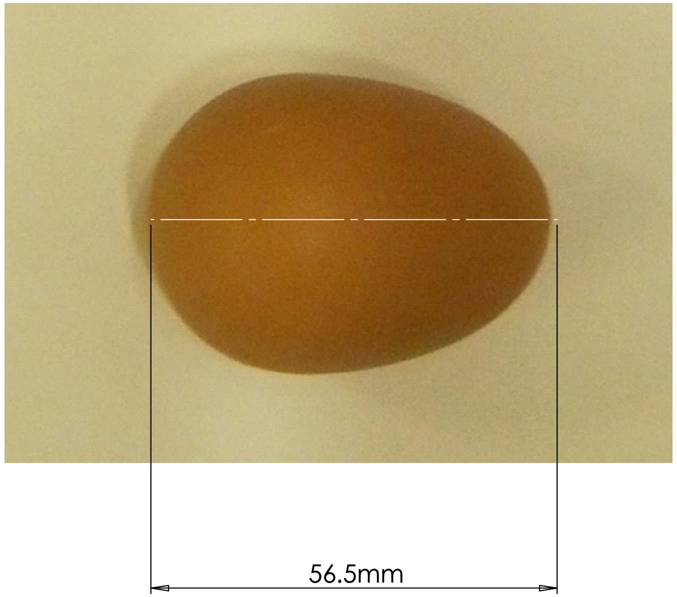
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS TOLERANCE: ±0.5 mm	NOTES:	DO NOT SCALE DRAWING	REVISION A
	NAME	DATE	
DRAWN	Thomas Baker	03 Feb 2020	

TITLE: Object 1

SHEET 1 OF 1

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS TOLERANCE: ±0.5 mm	NOTES:	DO NOT SCALE DRAWING	REVISION A
		TITLE: Object 2	
	NAME	DATE	
DRAWN	Thomas Baker	03 Feb 2020	SHEET 1 OF 1





UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN MILLIMETERS

TOLERANCE: ±0.5 mm

	NAME	DATE
DRAWN	Thomas Baker	03 Feb 2020

NOTES:

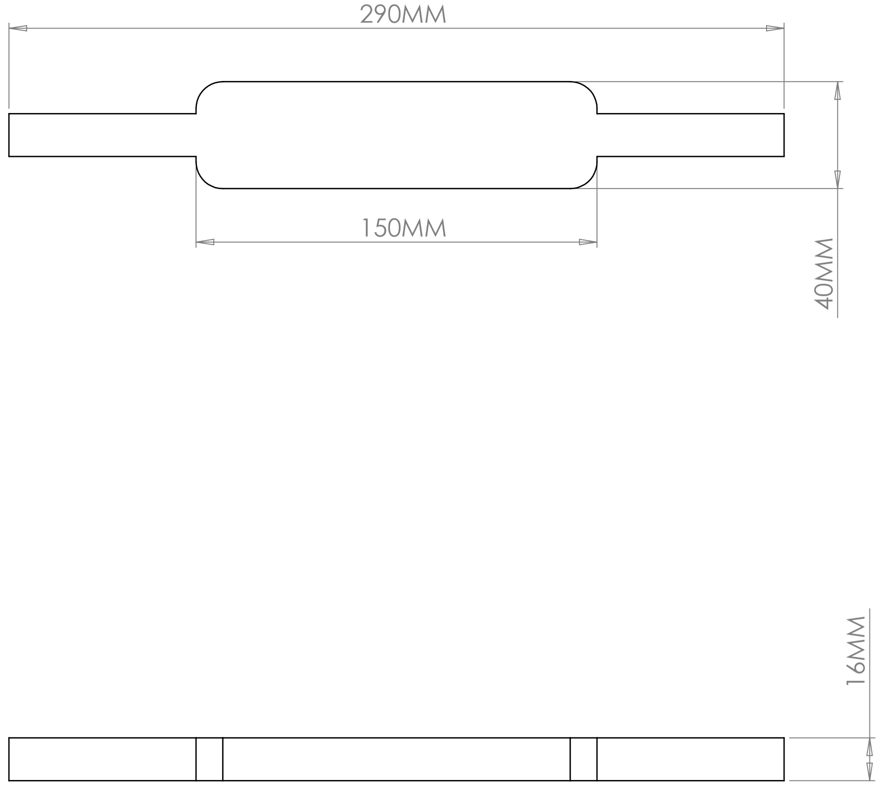
DO NOT SCALE DRAWING

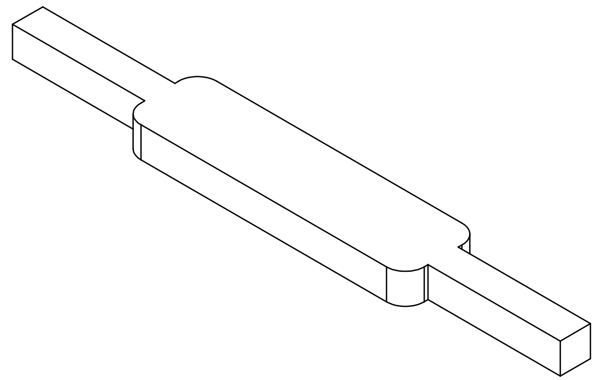
REVISION A

TITLE:

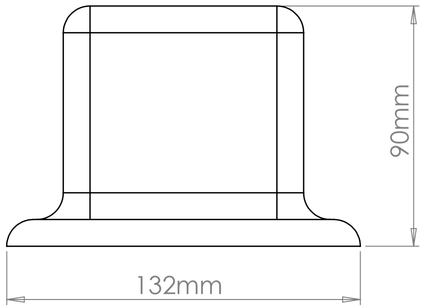
Object 3

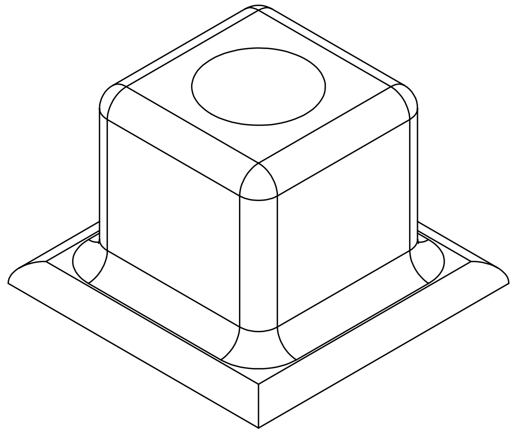
SHEET 1 OF 1

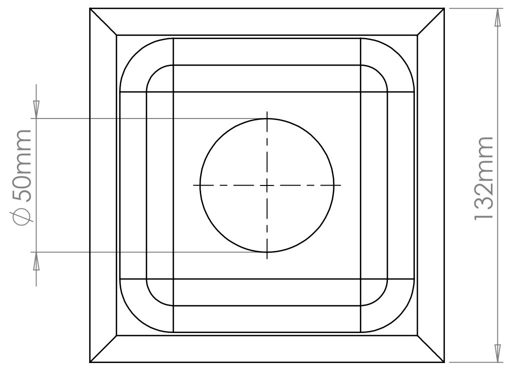




UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS TOLERANCE: ±0.5 mm	NOTES: 3D PRINTED OBJECT MATERIAL - PLA	DO NOT SCALE DRAWING	REVISION A
DRAWN — NAME: Thomas Baker — DATE: 03 Feb 2020		TITLE: Object 4	SHEET 1 OF 1







UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN MILLIMETERS

TOLERANCE: ±0.5 mm

	NAME	DATE
DRAWN	Thomas Baker	03 Feb 2020

NOTES:

3D PRINTED OBJECT
MATERIAL - PLA

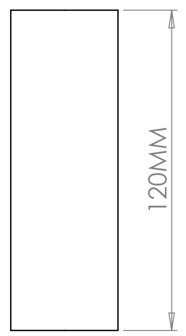
DO NOT SCALE DRAWING

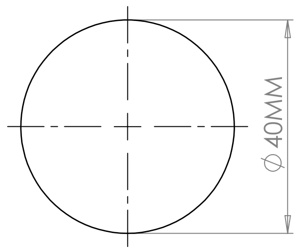
REVISION A

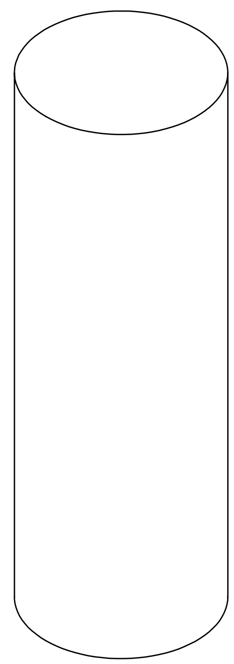
TITLE:

Object 5.1

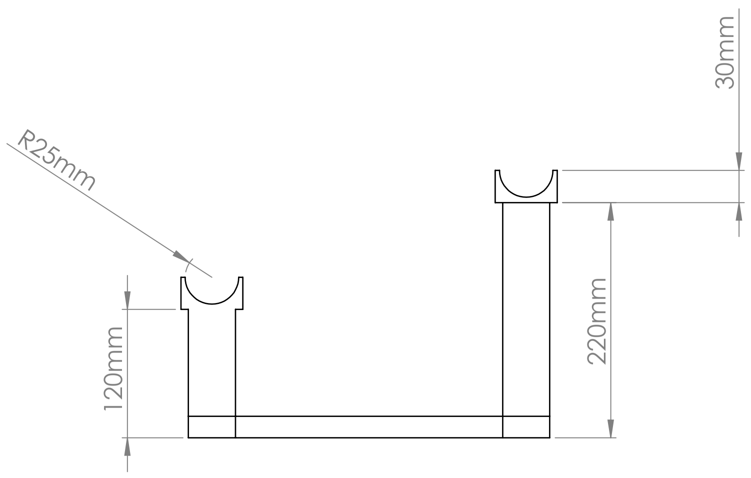
SHEET 1 OF 1

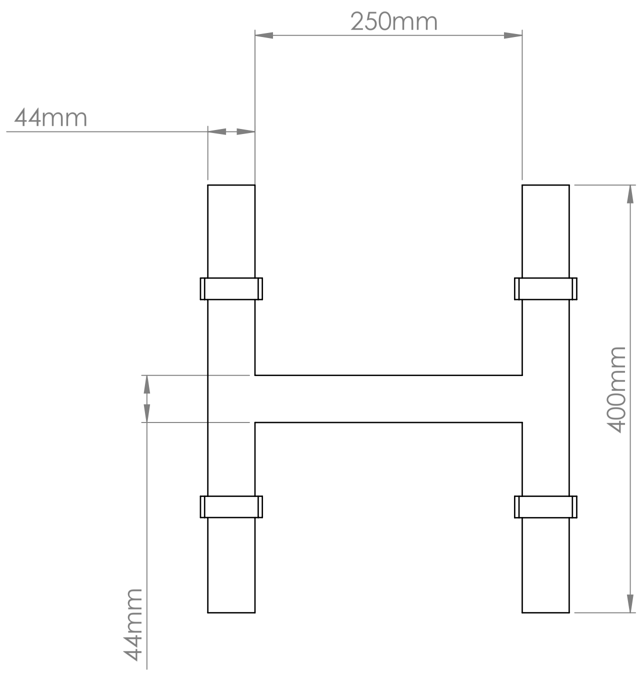


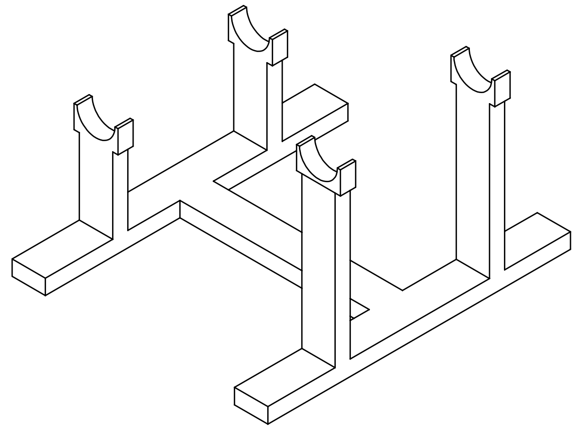




UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS TOLERANCE: ±0.5 mm	NOTES: 3D PRINTED OBJECT MATERIAL - PLA	DO NOT SCALE DRAWING	REVISION A
DRAWN — NAME: Thomas Baker — DATE: 03 Feb 2020		TITLE: Object 5.2	SHEET 1 OF 1







UNLESS OTHERWISE SPECIFIED:	DO NOT SCALE DRAWING	REVISION A
DIMENSIONS ARE IN MILLIMETERS	TITLE: Parrellel Bar	
TOLERANCE: ±0.5 mm		
DRAWN NAME: Thomas Baker	DATE: 03 Feb 2020	SHEET 1 OF 1