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# Development and assessment of a contactless 3D joystick approach to industrial manipulator gesture control

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## ABSTRACT

This paper explores a novel design of ergonomic gesture control with visual feedback for the UR3 collaborative robot that aims to allow users with little to no familiarity with robots to complete basic tasks and programming. The principle behind the design mirrors that of a 3D joystick but utilises the Leapmotion device to track the user's hands and prevents any need for a physical joystick or buttons. The Rapid Upper Limb Assessment (RULA) ergonomic tool was used to inform the design and ensure the system was safe for long-term use. The developed system was assessed using the RULA tool for an ergonomic score and through an experiment requiring 19 voluntary participants to complete a basic task with both the gesture system and the UR3's RTP (Robot Teach Pendant), then filling out SUS (System Usability Scale) questionnaires to compare the usability of both systems. The task involved controlling the robot to pick up a pipe and then insert it into a series of slots of decreasing diameter, allowing for both the speed and accuracy of each system to be compared. The experiment found that even those with no previous robot experience were able to complete the tasks after only a brief description of how the gesture system works. Despite beating the RTP's ergonomic score, the system narrowly lost on average usability scores. However, as a contactless gesture system it has other advantages over the RTP and through this experiment many potential improvements were identified, paving the way for future work into assessing the significance of including the visual feedback and comparing this system against other gesture-based systems.

*Relevance to Industry:* In industrial environments where the robots may need to be frequently reprogrammed through complex RTPs, companies must call on those with specialist training even to make minor adjustments. The presented system takes advantage of gesture control to allow for easy interaction with industrial robots, even for untrained operators.

## 1. Introduction

The rise of Industry 4.0 has seen increasing adoption of robots as replacements for traditional automated machines. This is thanks to the intelligence and multifunctionality of robots of the future, allowing them to be reprogrammed repeatedly for an increasing range of tasks. Collaborative robots are specifically designed for working closely with humans on common tasks with safety considerations being integral to their design. Collaboration between humans and robots allows the skills of both parties to be fully utilised in the manufacturing environment: robots can handle the repetitive strenuous tasks while humans handle more complex thought-intensive aspects (Colim et al., 2021a). This approach has already been found to be viable in areas where conventional automation is currently impossible (Walton et al., 2011).

Increasing collaboration between humans and robots is likely to lead to increasing expectations of the robots. This trend is already seen in smartphones, with new features and forms of interaction being key to creating competitive devices (Mohd Suki, 2013), and effective interaction has already been found to be vital for ensuring interaction leads to high performance in human-robot collaborative tasks (Green et al., 2008). This does not only apply to robots that are defined by their interactions, such as service and assistant robots, but all robots, as even programming could be defined as an interaction. Conventional industrial robot programming relies on the use of a Robot Teach Pendant (RTP): a device typically wired directly into the robot's controller and specialised for controlling robot motion. An example is pictured in

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*Abbreviations:* RTP, Robot Teach Pendant; RULA, Rapid Upper Limb Assessment; SDK, Software Development Kit; IMU, Inertia Measurement Unit; HMI, Human-Machine Interface; AR, Augmented Reality; SAR, Spatial Augmented Reality; RTDE, Real Time Data Exchange; SUS, System Usability Scale.

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**Fig. 1.** An example of an RTP: The ABB IRC5 FlexPendant (Wernholt, 2007).

Fig. 1. RTPs are often complex and require highly trained operators to be used effectively. Given that one of the advantages robots are bringing to automation is the ability to be re-programmed to do new tasks, limiting their use to specialists represents a hindrance to industries adopting robotics.

Common alternatives to RTPs include voice control (Pires, 2005; Tasevski et al., 2013; Maksymova et al., 2017), haptic controls such as joysticks (Jiang et al., 2013; Wagner et al., 2703)(which are sometimes integrated with modern RTPs, as seen in Fig. 1), and gesture controls (Grzejszczak et al., 2015; Zhang et al., 2019; Popov et al., 2019). These methods are more inclusive than the RTP as they take advantage of methods of interaction that are more natural to people. Voice control is often considered unsuitable for an industrial setting due to the high level of background noise and the safety concern of unwanted commands being accidentally picked up. Gestures are commonly used in natural speech to reinforce the speaker's ideas and can be used as a form of independent communication, for example, sign language. Firefighters use gestures at emergency scenes to signal movement commands for vehicles and ladders or hydraulic platforms, and similarly crane operators have a standard set of gesture signals for sending movement commands to the operator. The inability to communicate with gestures has been recognised as a drawback of remotely-operated surgery as they can no longer be used as a form of implicit communication between the surgeon and the supporting staff (Catchpole et al., 2019). This paper is not the first to identify the potential benefits gesture control could have for robot programming, and many have already been developed. These systems either utilise wearable devices fitted with sensors such as accelerometers and gyroscopes or contactless devices like RGB cameras and the specialised Kinect and Leapmotion.

In (Asokan et al., 2017), an example of a wearable glove device is presented as a control system for the teleoperation of rescue robots. The problems discovered perfectly illustrate the flaws with many wearable devices. Issues with the alignment of rotating joints caused excess stress and wear on the equipment. The calibration made it suitable only to a specific size of hands and was uncomfortable for the user to wear, and even with the proposed inclusion of an adjustable size, time will still be wasted when attempting to transfer control to another party. While the glove is a prototype so the issues are exaggerated, these problems are inherent to all wearable gesture devices and cannot be eliminated, only mitigated. In (Grzejszczak et al., 2015), an RGB camera is used with image processing to provide a contactless approach for teaching a robot targets and trajectories. While the pointing gesture is successfully recognised, the system's reliance on 2D image processing means it will only work in very specific conditions and had limited functionality.

Typically, specialised sensors such as the Kinect or Leapmotion are used for these applications due to their incorporation of depth information and wide range of built-in capabilities. The Kinect incorporates an RGB camera and infrared projector and detector with a host of onboard software enabling skeleton recognition and tracking, with Microsoft's own Software Development Kit (SDK) and numerous open-source drivers allowing this information to be accessed. An example of its use for industrial robot gesture control is shown in (Kaczmarek et al., 2021), where a comparison is made between using pre-set gestures and hand-tracking mimicry teleoperation for controlling an ABB IRB120. This study perfectly illustrates the two dominant control schemes for gesture systems: the use of pre-set gestures that must be recognised by the system and translated into a command, such as "move left", "move right" etc., and having the robot mimic the hand movements of the operator. Their work determined that the mimicry approach suffers from restrictions on speed and workspace size and though pre-set gestures tended to allow more accurate movements, they are less intuitive and hard to apply without overcomplication, a point which is also made in (Grzejszczak et al., 2015). The system in (Du et al., 2018) takes this comparison to the next level, improving the accuracy of the mimicry approach by applying an Interval Kalman filter and Particle filter to the Kinect data and supporting it with a wearable Inertia Measurement Unit (IMU). An overcomplicated pre-set gesture scheme is avoided through the inclusion of vocal commands. Pre-set gestures were still found to be better for fine control, but this system's application in industry is limited by its use of a wearable device and voice control which will suffer from the issues mentioned previously.

The Leapmotion is a device incorporating infrared projectors and detectors and is specially designed to capture hand and finger positions and orientations. It is almost as popular for applications in robotics as the Kinect, for both mimicry teleoperation as shown in (Bassily et al., 2014) and (Hernoux et al., 2015) and pre-set gestures combined with mimicry in (Zhang et al., 2019). Part of the Leapmotion's popularity stems from its advertised sub-millimetre accuracy, although the research in (Hernoux et al., 2015) finds that this is not the case and that the accuracy is dependent on the distance from the sensor with sub-millimetre being the best-case scenario. Once again (Hernoux et al., 2015), finds the mimicry approach suffers from speed issues, while (Bassily et al., 2014) finds it suffers from low accuracy due to tremors in the user's movements, which is reflected in the system as noise and proposes applying a threshold to movements to reduce this. The study in (Zhang et al., 2019) finds a solution to the mimicry approaches workspace limitation issue by using a "clutch" mode, allowing the operator to reposition their hand within the Leapmotion's envelope without the robot copying, a bit like picking up a computer mouse once it has reached the edge of the desk and repositioning it to allow further travel.

A final example of the Leapmotion's use for industrial robot control is presented in (Tang and Webb, 2018). Again, the goal is the replacement of the RTP, but this research approaches the system from an ergonomic and usability perspective rather than purely technical. This is not a consideration that has been taken in any of the papers presented previously and potentially represents a significant gap in the literature, particularly given that work-related musculoskeletal disorders account for the majority of reported occupational diseases in developed countries (Maurice et al., 2017). Further research reveals a similar trend as found in this review: many gesture control systems may be technically brilliant and innovative, but rarely consider the impact on the operator from extended use. This is summarised well by a quote from (Catchpole et al., 2019) relating to robotic-assisted surgery: "Robotic techniques have revolutionised many procedures … [However, the] impact of these novel techniques on the console and assisting surgeon's mental and physical workload is only just starting to be explored".

The developed system in (Tang and Webb, 2018) outperforms the RTP, but the lack of feedback, either visual or tactile, is recognised in the paper as a limitation of the work and is proposed for future development. This shows one of the potential drawbacks of the contactless approach, as an example researched in (Okamura et al., 1998) using a joystick found that the inclusion of vibration and force-feedback improved task execution and perception in human subjects. However, work using ultrasonic vibrations to allow for mid-air tactile feedback has been progressing steadily and is showing promising results (Tashiro et al., 2009). Building on previous work using directed air jets, arrays of ultrasonic transducers can be used to focus inaudible soundwaves on a specific point in 3D space and elicit the sensation of touch. This focal point can be moved rapidly, allowing for the simulation of different shapes and textures, potentially allowing for advanced tactile feedback to be provided with contactless systems (Rakkolainen et al., 2019).

Providing visual feedback has also been found to improve accuracy in object-grasping tasks (Bozzacchi et al., 2014). Screen-based feedback is already commonplace in industrial settings in the form of Human-Machine Interfaces (HMIs) which assist an operator in visualising the state of the system they are using (Gong, 2009). This is particularly important for contactless systems to allow the operator to understand the consequences of their movements. An advanced example of feedback for a gesture control system is presented in (Chan et al.,) where Augmented Reality (AR) is integrated with tactile feedback for the task of programming robot trajectories. The inclusion of AR allows the operator to see their targets and desired path in 3D, and even watch a render of the virtual robot complete the programmed tasks to ensure it all works as planned. This particular system uses an AR headset so could not be considered contactless, but Spatial Augmented Reality (SAR) systems use digital projectors to create a similar effect and have already been found to improve accuracy and error rates in industrial tasks (Uva et al., 1007).

To summarise the lessons taken from the above paragraphs, it should hopefully be clear that gesture control is advantageous for an industrial environment and why contactless technology may be preferable to wearable. A range of devices can be used for contactless systems, both for collecting data about the operator's position and providing them with vital feedback. Gesture systems fall under the categories of either pre-set or mimicry control, where pre-set systems can allow more accurate control but quickly become overcomplicated while mimicry systems are easier to learn and use but suffer from restrictions on the workspace and speed. Additionally, most existing research assesses gesture systems on accuracy or time spent on a task without considering usability and ergonomics, which should be fundamental considerations for any system destined to have a practical application.

This paper presents the findings from developing and assessing a novel gesture control scheme that was designed to incorporate the benefits of both pre-set and mimicry approaches while avoiding their respective drawbacks.

### 1.1. Research objectives

- Create a prototype contactless joystick system for the UR3 collaborative robot.
- For the developed system to avoid the previously mentioned limitations of the pre-set gesture and mimicry approaches to gesture control.
- The system should be intuitive and easy to learn even for people with no previous robot experience, but still offer some of the most important control capabilities included with the RTP such as movement and basic programming.
- Ergonomics, which is often overlooked in robotic gesture control studies, will be a key consideration in the system's design and assessment.

## 2. Material and methods

### 2.1. System description

#### 2.1.1. Method of control

The design utilises the direction and magnitude of the user's movements as input to determine robot motion, as this is what makes the mimicry approach easy to use. To avoid the limitations on the workspace, thresholds were placed on this motion that when crossed would result in continuous motion in the desired direction. The limitation on speed was addressed by having multiple thresholds in a single direction, allowing for variable speed control. This design essentially matches the core concept of a joystick, but where the positional data of the user's own hand is the stick. Joysticks are already common for movement controls in everything from industrial machines to planes and videogame consoles and can be used for robot motion too as shown by the joystick on the RTP in Fig. 1. Joysticks typically provide 2D control, but since the user's hand can be tracked in three dimensions this allows for three values to be controlled at a time. Previous work has already found a physical 3D joystick for controlling a robotic arm reduced task completion time and had a reduced learning curve compared to the other tested modalities (keyboard and 2D joystick) (Jiang et al., 2013).

To provide a comparable level of control over a six jointed manipulator to an RTP, the system needed to control cartesian movement of the robot's end-effector in X, Y and Z, rotation around X, Y and Z, and the angles of the six individual joints. This is a total of twelve different values, and since a 3D joystick can only control three values at a time, four different modes were required. A simple pre-set gesture scheme was developed to allow for changing mode and some basic programming capabilities, such as saving and editing movement instructions and then replaying them. To avoid overcomplication, a numeric association between each command was created allowing the command to be relayed by displaying the appropriate number of fingers. For example, there are four movement modes, and the numbers one to four can be displayed on one hand. This allows the positional data of the hand to work as the joystick, while the fingers of the same hand control the mode resulting in all movement-related operations being completable with one hand. A stop mode was included if the hand is flat (with all fingers and thumbs extended) to allow the hand to be moved without any consequence. The other hand is then free to display the numbers corresponding to the programming instructions, as shown by Table 1.

#### 2.1.2. System architecture

The technology used to implement this control scheme included a Leapmotion, UR3 collaborative manipulator, and a laptop to run the software. The program was developed in C# allowing it to take advantage of the Leapmotion's v3.2 SDK, TCP connectivity required for communicating with the UR3, and Windows Forms for a GUI (Graphical User Interface). A basic diagram is shown below in Fig. 2.

**Table 1**
The associations between the number of fingers held up on each hand and the desired command.

| Numeric Associations with Commands | | | |
|---|---|---|---|
| Left Hand | | Right Hand | |
| 1 Finger extended | Save current pose. | 1 Finger extended | Cartesian Mode |
| 2 Fingers ext. | Clear the list of instructions. | 2 Fingers ext. | Rotation Mode |
| 3 Fingers ext. | Play the saved instructions. | 3 Fingers ext. | Joints 1, 2 & 3 |
| 4 Fingers ext. | No Input | 4 Fingers ext. | Joints 4, 5 & 6 |
| 4 Fingers & Thumb ext. | No Input | 4 Fingers & Thumb ext. | Stopped Mode |

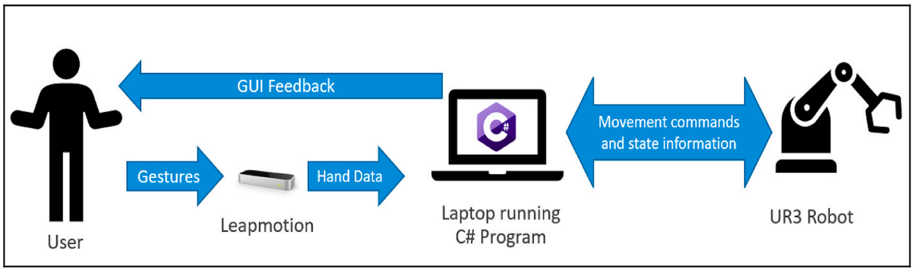


**Fig. 2.** Basic system architecture.

### 2.1.3. *Gesture recognition and Robot motion*

The program utilises the capabilities of the Leap SDK v3.2 to track and react to the user's gestures. The Leapmotion captures frames at 120Hz (Leap Motion Controller TM, 2021) and the SDK provides an event that is triggered on each new frame's arrival, allowing the system to react continuously to new data. The first reaction that occurs involves interpreting the data sent with the frame, such as if the hand is the left or right, how many fingers are extended and the 3D position of the hands from the Leapmotion's coordinate frame. The number of extended fingers are counted, and the appropriate programming instruction or movement mode is selected depending on the hand. The position of the right hand is then compared against the thresholds set for each direction and used to determine what motion, if any, should occur.

The method of conveying these instructions to the UR3's controller requires two TCP connections over an ethernet cable. The robot's documentation describes that there are three ports available for receiving URScript commands: 30001, 30002 and 30003. A fourth port, 30004, is provided as the best way to receive state updates, such as positions and temperature etc., from the robot in real time. These connections are established when the program is started, one to port 30002 and the other to port 30004. URScript commands stored in a string are converted to bytes and then sent to port 30002, which allows these commands to be executed without any program necessary on the controller to interpret the instructions. Port 30004, also known as the Real Time Data Exchange (RTDE) interface, is used to retrieve the current state of the robot. For example, when the gesture to save a waypoint is detected, the current joint angles of the robot will be requested from port 30004 and saved, allowing them to be used in a URScript joint-movement command. A diagrammatic representation of the code is shown in Fig. 3.

### 2.1.4. *Ergonomic requirements*

To keep ergonomics central to the system's design, the Rapid Upper Limb Assessment (RULA) (McAtamney and Nigel Corlett, 1993) was used to help set thresholds and develop the system's working envelope. This assessment scores postures based on the angles the limbs are held at with a focus on the arms and upper body, which are the main areas used for this system. RULA has been used in previous robotics studies such as

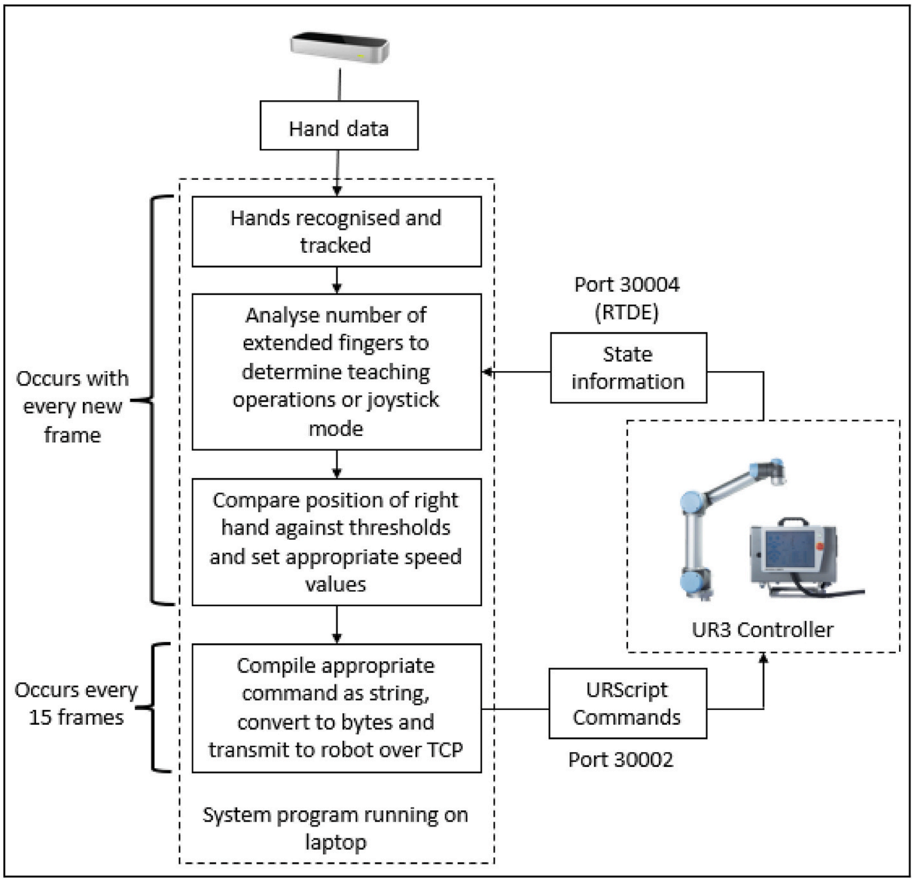


**Fig. 3.** A diagram displaying the translation of Leapmotion data to robot motion.

in (Tang and Webb, 2018) where it evaluates a similar gesture control system and in (Colim et al., 2021b) for assessing a collaborative robotic workstation. Fig. 4 shows how the scores for the arms are calculated, which are then combined with the scores for the other parts of the body to derive an overall score between 1 and 7. The consequence of this score is shown in Table 2.

Fig. 4 shows that the optimal score for the arms can be achieved by having the upper arm down by the side of the torso with the forearm extended at around 90°. By manipulating the thresholds of the system to influence its working envelope, the user's arm can be kept in this "sweet spot" and minimise the risk of musculoskeletal injury, as illustrated in Fig. 5.

### 2.1.5. *Visual feedback – GUI development*

It was established previously that a form of feedback for the operator is an important inclusion for contactless systems. As such, a GUI was developed to assist the user in understanding the state of the system. The GUI was required to display the positional data of the user's hand with reference to the thresholds, the mode the system was currently in and the list of commands that were currently saved. It was determined that the mode and commands could easily be displayed as text, but a diagrammatic approach would be preferable for the positional data. The design of this diagram was derived from the visual feedback a user would receive if looking down on a physical joystick from above, where a cursor would represent the "stick" and the thresholds can be shown with lines along the axes. This type of diagram has already been used to represent directional information that includes magnitude in the form of g-force gauges in performance vehicles. The similarity between the two is illustrated in Fig. 6.

This design was then drawn and programmed using a Windows Forms application that is updated with the rest of the system every time a new frame arrives from the Leapmotion. As the GUI is a 2D representation of 3D positions, two diagrams were necessary to display all the

**Table 2**
The level of risk associated with each value of the RULA score.fx1.

| Score | Level of Risk |
|---|---|
| 1 – 2 | Negligible risk, no action required. |
| 3 – 4 | Low risk, change may be needed. |
| 5 – 6 | Medium risk, further investigation required, change soon. |
| 7 | Very high risk, implement change now. |

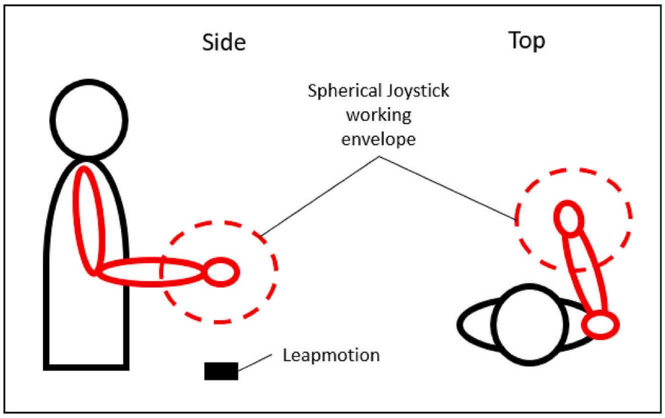


**Fig. 5.** The proposed working envelope of the joystick system to minimise the RULA arm score.

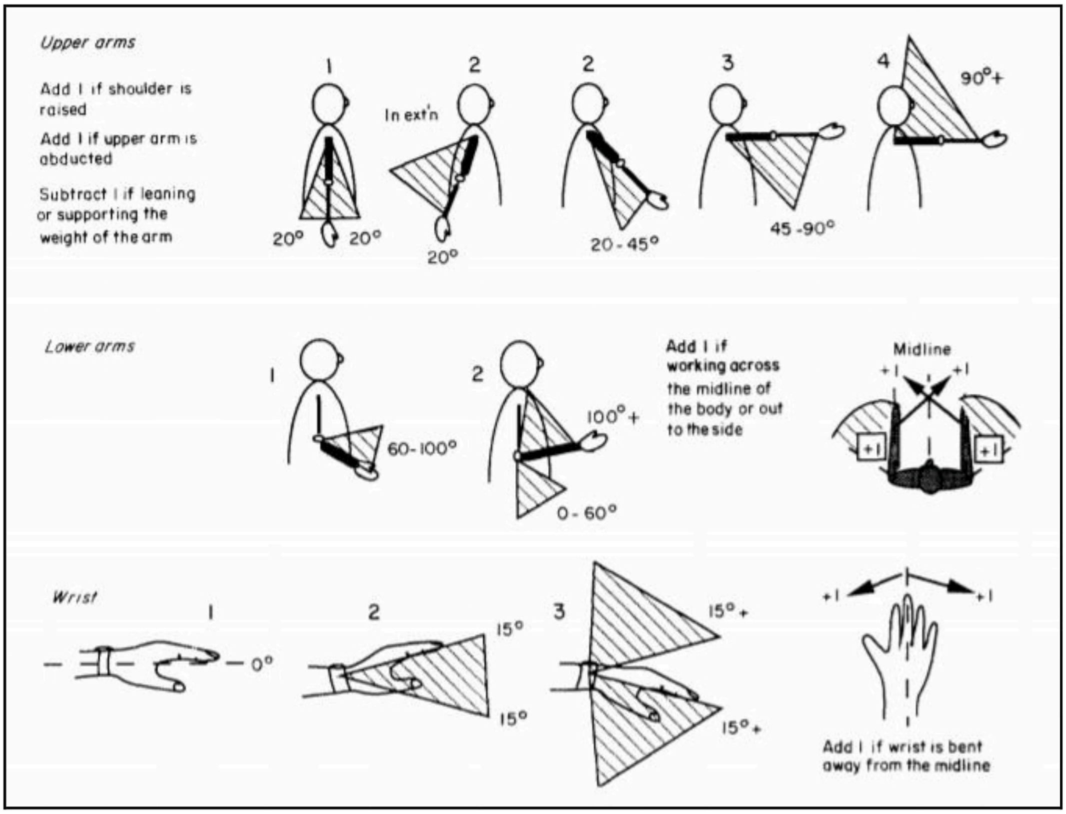


**Fig. 4. A diagram from the original paper proposing the RULA tool showing how the scores for the arms are determined** (McAtamney and Nigel Corlett, 1993).

**Fig. 6.** A joystick shown from above (left) (Infrared Remote Control for All, 2021) and an example of a g-force gauge used in motorsport (right) (VI Meter, 2009).

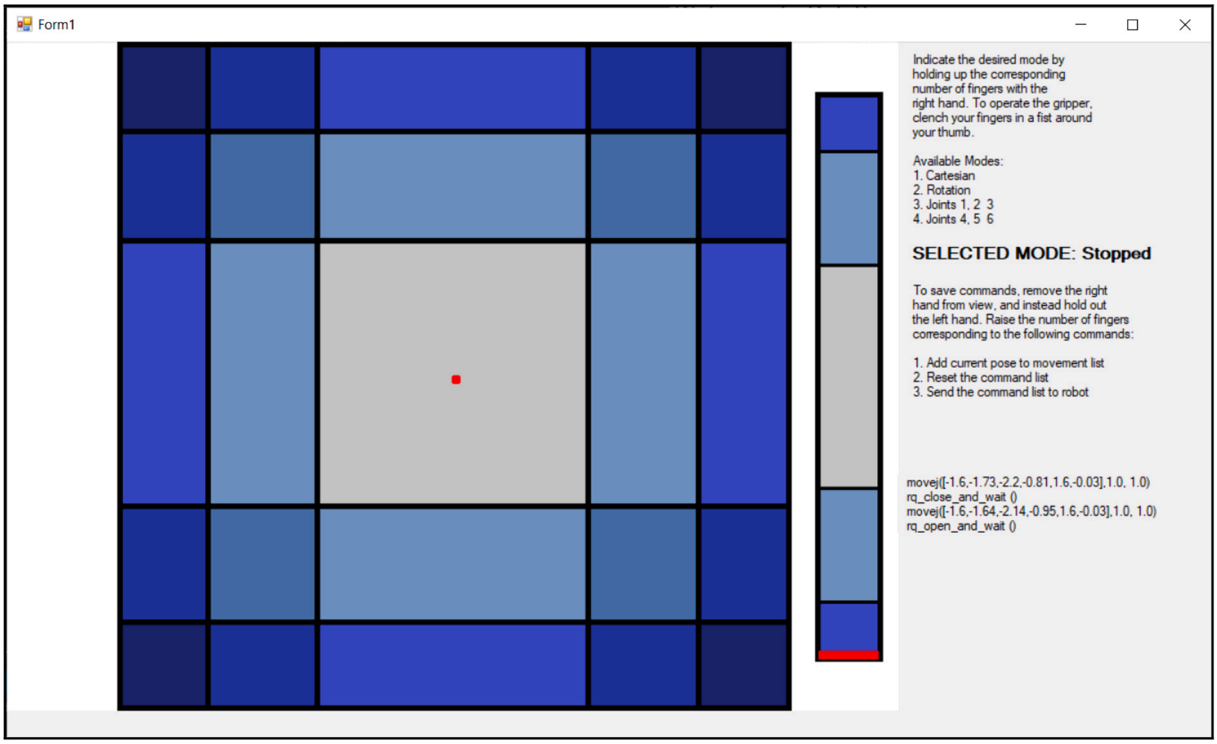
information where the X and Y positions are represented on the g-force gauge inspired diagram while Z is represented on a separate linear diagram. Colour-coding was used to help users differentiate between the central dead-zone and the motion thresholds, with the colours becoming more concentrated as the speed increases. Along with the mode and command list, some basic instructions were included as text making it potentially possible to use the system without any prior training. The resultant GUI is displayed in Fig. 7.

## 2.2. Methodology

To obtain a comprehensive evaluation of the system, key criteria against which it would be assessed were selected based on the design goals. These goals included providing complete control over the robot's movement and basic programming, making the system easy to learn and use, and ensuring the risk of injury from prolonged use is minimised. The criteria can therefore be summarised as functionality, usability, and ergonomics. The UR3's RTP was used as a point of comparison, a picture of which is included in Fig. 8.

### 2.2.1. Ergonomic assessment

To assess the ergonomics of the system, the RULA assessment that was central to the system's design was used to provide scores for both the contactless joystick and the RTP. This method of assessment was chosen due to its focus on the arms, as both the RTP and gesture system only rely on movement of the arms to operate; neither system imposes any limit on how the user wishes to pose the rest of their body. Additionally, the purpose of the system is making quick adjustments rather than long-term programming. For this reason, duration-based ergonomic assessments were deemed beyond the scope of this initial analysis as the postures themselves pose the greatest risk to the user. Six poses for assessment were chosen by extending the hand to the most extreme points of the system's working envelope along the X, Y and Z axis as from the analysis performed in Subsection 2.4, these would be the areas most



Indicate the desired mode by holding up the corresponding number of fingers with the right hand. To operate the gripper, clench your fingers in a fist around your thumb.

Available Modes:
1. Cartesian
2. Rotation
3. Joints 1, 2 3
4. Joints 4, 5 6

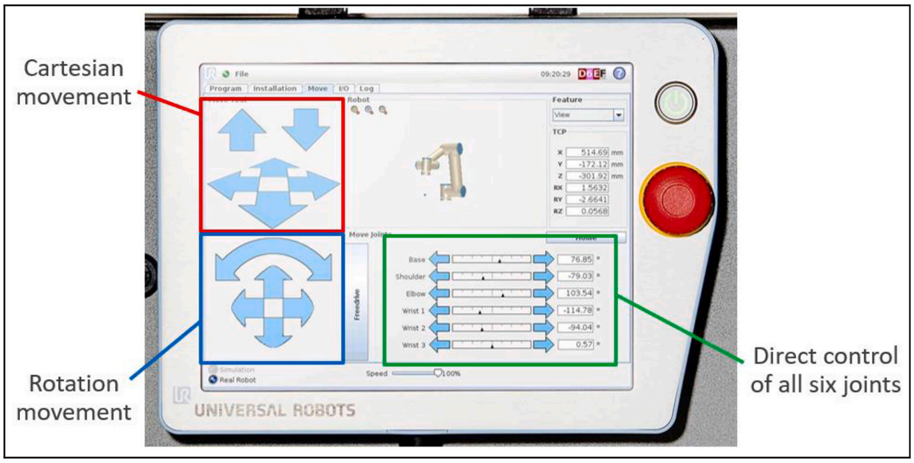
**SELECTED MODE: Stopped**

To save commands, remove the right hand from view, and instead hold out the left hand. Raise the number of fingers corresponding to the following commands:

1. Add current pose to movement list
2. Reset the command list
3. Send the command list to robot

```
movej([-1.6,-1.73,-2.2,-0.81,1.6,-0.03],1.0, 1.0)
rq_close_and_wait ()
movej([-1.6,-1.64,-2.14,-0.95,1.6,-0.03],1.0, 1.0)
rq_open_and_wait ()
```

**Fig. 7.** The GUI design. The leftmost diagram shows the X and Y positions of the user's hand while the rightmost one shows Z, or the elevation of the hand from the Leapmotion. The text down the right hand side shows the mode, command list and some basic instructions.



09:20:29

X 514.69 mm
Y -172.12 mm
Z -301.92 mm
RX 1.5632
RY -2.6641
RZ 0.0568

Base 76.85 °
Shoulder -79.03 °
Elbow 103.54 °
Wrist 1 -114.78 °
Wrist 2 -94.04 °
Wrist 3 0.57 °

Speed 100%

**Fig. 8.** The UI of the UR3's RTP with labelled controls.

likely to increase the RULA score and thus the risk. The right side of the body was assessed as the right arm is the one most heavily used to operate the system. Multiple participants were not required for this assessment as the scores should be identical for all users, provided they have set up the Leapmotion correctly, allowing the ergonomic assessment to be performed separately from the task-based experiment. Analysis of one researcher's postures when using the joystick and RTP was carried out, so for this assessment the independent variable was the method of control, and the dependant variable was the RULA score.

### 2.2.2. *Experiment description*

For the remaining assessments, an experiment was conducted using voluntary participants from a range of backgrounds and with a variety of experience with robots. For the experiment, a gripper was attached to the robot so additional gestures were required for the control and programming. Clenching a fist with the right hand would open or close the gripper, and the same gesture with the left hand would save the instruction to either open or close the gripper to the command list.

*2.2.2.1. Participants.* Prior to beginning the experiment, ethical approval was obtained through the Cranfield University Research Ethics System. Nineteen people from the general populations of Cranfield University and Hertfordshire County participated in this experiment. Their ages ranged from 21 to 57 with a mean of 27. There were 15 males and 4 females, with 17 being right-handed and 2 being left. When asked about previous experience with robots, 2 described themselves as expert operators, 6 had some experience, and 11 had never used one before.

*2.2.2.2. Physical setup.* The experiment took place in a walled laboratory environment with the UR3 mounted on a tabletop. The UR3 was attached to the table such that its X and Y axes were at a diagonal angle to the rest of the table to accommodate for the placement of the other objects. Approximately 30 cm in front of the UR3 was a section of pipe with a diameter of 36 mm and a rack of four holes with diameters of 52 mm, 48 mm, 44 mm and 40 mm, as pictured in Fig. 9. The Leapmotion and laptop showing the GUI were placed on a separate table that was also angled to account for the UR3's axes. A full top-down diagram of the layout is included in, with the RTP's position omitted as due to the length of its cable the participant was free to position themselves wherever they liked.

*2.2.2.3. Task description.* The task for the participants to complete involved using the UR3 to insert a section of pipe into four holes of decreasing diameter, going from easiest to hardest. Participants were allowed up to three attempts per hole before moving on, where the conditions for failure include colliding with the top surface of the rack, moving the rack, dropping the pipe into an unrecoverable position, causing the robot to enter a protective stop or shutdown state, or verbally requesting a reset. The independent variable was the method of control, and the dependent variables were the success or failure of each hole, number of attempts and the time each one takes. This task was selected as it forces the participants to explore movement in all three

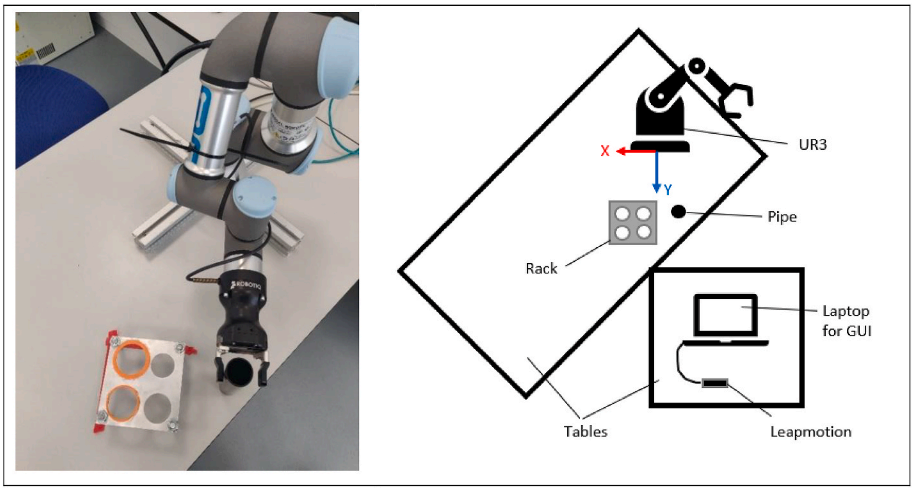


**Fig. 9.** A photo and top-down diagram showing the layout of the experiment set-up.

axes, allows quantitative data to be collected in the form of the accuracy and time-taken, and bears similarities to tasks performed regularly in industry. Pick and place tasks are a common application of robots in industrial environments and have been used to assess alternative methods of control in the past, such as in (Wagner et al., 2703). The accuracy of the motion can also be very important for certain industrial tasks, and this has been measured in the past by having the robot grip a pen and then getting the participants to move the robot to place a mark on a sheet of paper with a target drawn on it as quickly as possible (Jiang et al., 2013). The pipe insertion task aims to combine a pick and place style operation with avoidance of an obstacle in the form of the rack, and an assessment of the accuracy through the time taken and number of attempts required for each hole as the diameter decreases.

*2.2.2.4. Procedure.* First, a consent form was provided to each participant along with a questionnaire to collect demographic information prior to participation (this can be found in Appendix A). A scripted briefing, which can be found in Appendix B, was then given to each participant along with a demonstration of the first system. The order in which the systems were introduced was varied to ensure this would not interfere with the results. Participants were given up to 10 minten minutes to practice after each system has been demonstrated, and then the task was explained. Upon completing the task with the first system, the participant was given the usability questionnaire. This process was then repeated with the second system.

*2.2.2.5. Usability aspect.* To compare the systems from a usability perspective, the System Usability Scale (SUS) was used to allow the participants to provide a score by which the systems could be compared. The SUS questionnaire is a long-established method for assessing usability and the questionnaire used can be found in Appendix C (Brooke, 1996). The questionnaires were provided immediately after using each system to ensure that the participant's experience was fresh in their mind. For this aspect, the independent variable was once again the method of control, while the dependent variable was the usability score.

## 3. Results

### 3.1. Pre-experiment evaluations

#### 3.1.1. System functionality

Prior to beginning any further assessments, the basic functionality of the system was tested. This not only allowed for verifying all the desired functionality, but also making small adjustments to the numeric values such as thresholds and movement speeds to optimise the system further. The full list of desired functionalities that were checked is as follows: cartesian movement, rotational movement, joint movements, gripper control, saving movement commands, saving gripper commands, resetting the command list and playing-back the command list.

These functions were tested both in the URSim simulation environment and on the physical UR3 robot. When provided with the correct IP address, the system successfully made the connection in both cases and allowed for control to begin. No setting up on the robot itself is required beyond ensuring it is switched on, initialised, and connected to the laptop through an ethernet cable. All the movement functions worked as intended, with only a few adjustments being made to the speed values. Through this testing it was found that the system successfully delivered all desired functionality.

#### 3.1.2. Ergonomics – RULA score

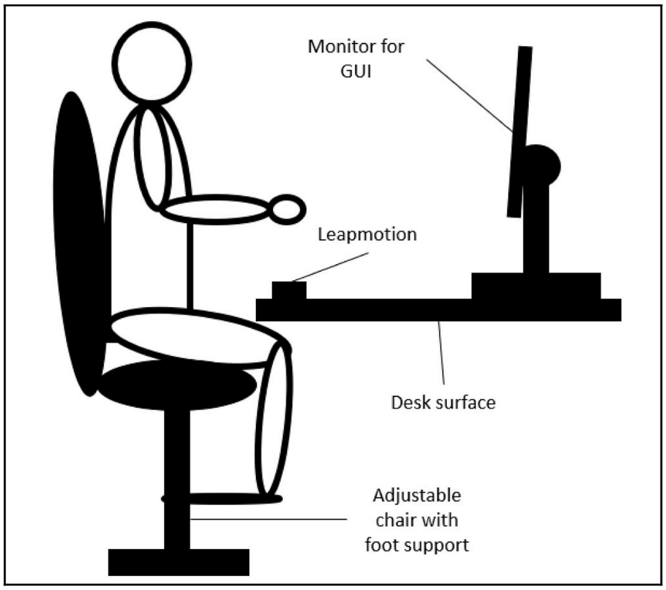


**Fig. 10.** The optimal posture for using the contactless joystick system.

With the operator seated and the Leapmotion and GUI in the optimal positions (pictured in Fig. 10), the upper arm, lower arm and wrist scores were all at the minimum of 1. The force/load score was 0 as there is no requirement to hold any object. The muscle use score is subject to context, as it is considered 0 unless the posture is mainly static or if a certain action is repeated four times in 1 minone minute. The task the operator is doing may cause these conditions to be true, but on its own the system has no requirement that either be true so this score can also be 0. This gives an overall arm and wrist score of 1, meaning the risk is negligible. Even if the muscle load score is increased to 1 by the task the operator is completing, this only increases the arms score to 2 which is still acceptable. The neck, trunk and legs also receive scores of 1. Once again, the force/load score will be 0 and the muscle use score can be 0 or 1 depending on the task. Again, this gives the overall score of either 1 or 2. Assuming the worst-case scenario of both scores being 2, this gives an overall RULA score of 2 which is still considered to be of negligible risk.

The UR3's RTP was analysed to provide a point of comparison. A crucial difference here is that the RTP must be held by the operator, increasing the force/load score by 1 or potentially further depending on the weight of other devices. This also alters the posture of the arms significantly, requiring the lower arms to be raised at a greater angle with a large twist in the wrist. This posture is also mainly static, and when put together this gives an overall arm and wrist score of 5. The neck, trunk and legs similarly receive an overall score of 5, giving an overall RULA score of 6. This result is further supported by the same assessment carried out in (Tang and Webb, 2018), and suggests the RTP presents a medium risk. Fig. 11 shows a graphical comparison of the two results.

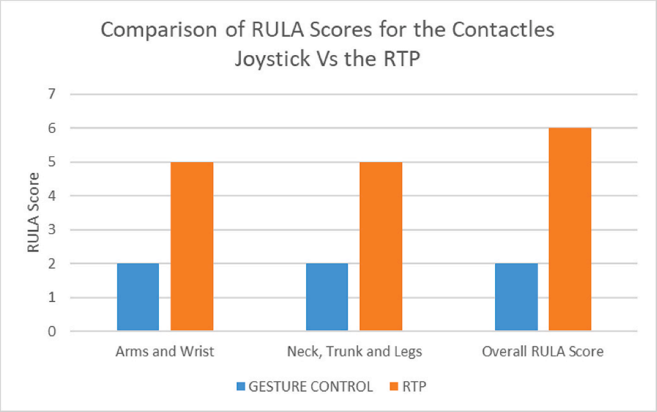


**Fig. 11.** A bar chart to compare the RULA score of the Contactless Joystick and the UR3's RTP.

### *3.2. Experiment results*

#### *3.2.1. Time and accuracy*

All nineteen participants completed all four holes using the RTP, while eighteen out of nineteen participants completed all four holes with the gesture control, with one failing the final 4 mm tolerance hole. The frequencies of the number of attempts per hole are shown in Fig. 12. Using the RTP, participants generally cleared each hole on their first attempt while with the gesture control system it was more common that two or three attempts would be required, particularly as the difficulty increased.

Fig. 13 shows the average time taken to complete each hole. With the RTP, the 16 mm took an average 21.7 s (SD = 10.6), the 12 mm took 18.9 (SD = 8.2), the 8 mm took 18.5 (SD = 8.1) and the 4 mm took 20.8 (SD = 11.4). With the gesture control, the 16 mm took 44.2 (SD = 29.6), the 12 mm took 40.5 (SD = 14.7), the 8 mm took 45.0 (SD = 28.9) and the 4 mm took 43.0 (SD = 21.1). On average, each hole took 23.1 s longer to complete using the gesture control system.

#### *3.2.2. System usability*

Fig. 14 shows the results calculated from the questionnaire using the method described in (Brooke, 1996) to give a score out of 100. First the score contributions from each question are summed, where each contribution ranges between 0 and 4. For odd-numbered questions, the score contribution is the scale position minus 1. For even-numbered questions, the contribution is 5 minus the scale position. The sum of these scores is then multiplied by 2.5 to obtain the overall value. The RTP received an average score of 80.4 (SD = 13.4) while the gesture control scored 66.4 (SD = 21.3). By looking at Fig. 14 and the high standard deviations, these scores varied greatly across participants with some favouring the gesture control but more favouring the RTP. Generally, those who gave both systems similar scores tended to favour the RTP slightly.

SUS scores are commonly converted into percentile ranks to allow for comparison to other products, shown below in Fig. 15 (Brooke, 2013). The three included scales are Acceptability Ranges, Adjective Ratings and a Grade Scale. From this it can be seen that the RTP's score of 80.4 makes it "Acceptable", "Good" and grade "C/B". The gesture control's score puts it at the higher end of "Marginal" and "OK", and grade "D".

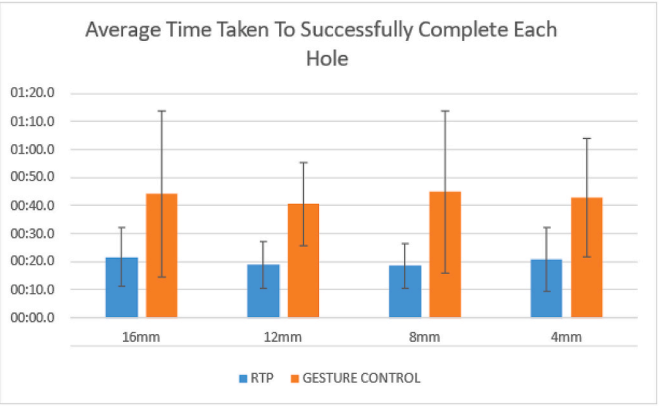


**Fig. 13.** A bar chart showing the comparison of the average times participants took to complete each hole with both systems.

#### *3.2.3. Results divided by skill*

By collecting the participants' level of familiarity with robots, it was possible to divide the results by skill to see how much influence this had on the use and perception of the systems., and Fig. 16 shows the timing results divided in this way. Those who had never used robots were 21.2 s slower with the gesture control system on average, those with some experience were 31.1 s slower and those with expert skill were only 8.4 s slower. Fig. 17 shows the usability results split by skill. Those who had never used robots gave the RTP an average score of 78.3 (SD = 14.1) and gave the gesture control 61.1 (SD = 24.2). Those with some experience gave the RTP 83.8 (SD = 15.2) and gesture control 72.1 (SD = 17.6). The expert participants gave the RTP 82.5 (SD = 7.1) and gesture control 78.8 (SD = 1.8). From these values and the charts below, the scoring by those with no previous experience was far more volatile with a large gap between the two averages. On the other hand, those with some or expert experience ranked the systems far closer.

## 4. Discussion

The evaluations show that the system was successfully able to achieve its design goals of providing all desired functionality in an ergonomic way, even for those who had never used a robot before. In the ergonomic scores the gesture system was found to have a far lower risk

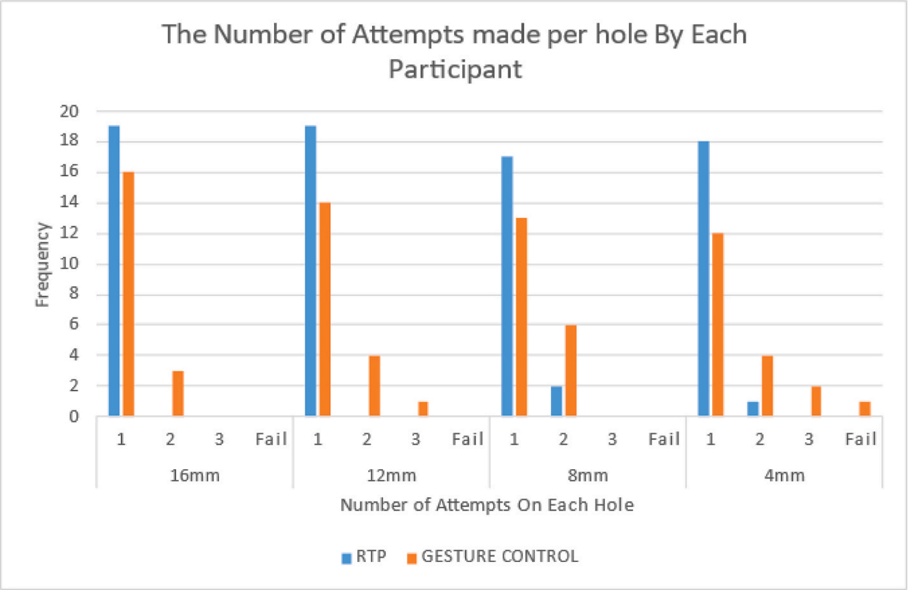


**Fig. 12.** A chart showing the frequencies of the number of attempts per hole across all participants.

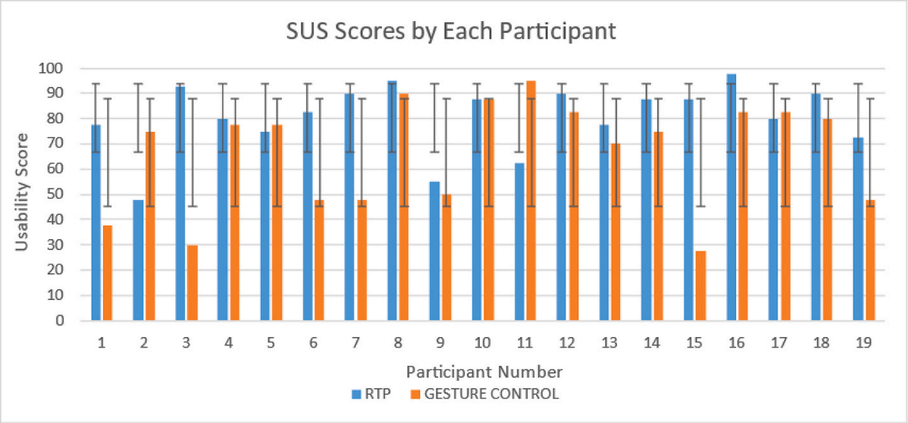


**Fig. 14.** **A scale showing the conversion of a raw SUS score into different rankings** (Brooke, 2013).

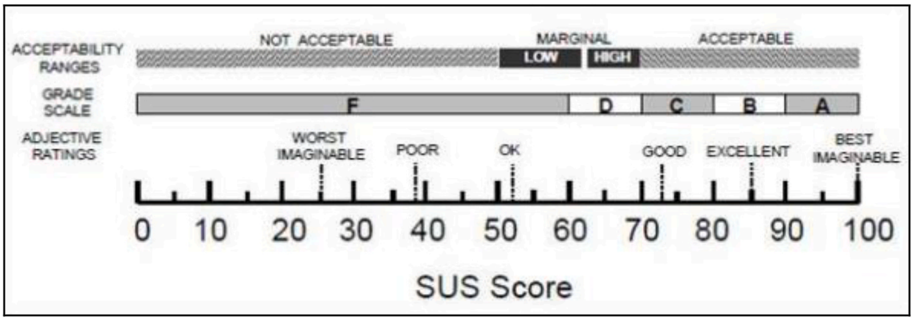


**Fig. 15.** The calculated SUS scores from each participant for both systems.

than the RTP, but the opposite was true for the usability scores with people generally favouring the RTP. The gesture system also shows a minor improvement on the RULA score of the system presented in (Tang and Webb, 2018), the only other paper to offer such analysis of a robotic gesture system. However it is important to note that RULA does not offer a complete ergonomic analysis, which represents a limitation on the ergonomic aspect of this study. While it is a widely-used tool, it does not have the evidence-base for predicting adverse musculoskeletal health outcomes for hand activities that other tools such as the Strain Index possess. Further experimentation with more participants and a wider range of tools would be required to definitively prove that the gesture system is safer than the RTP.Experience level was clearly an influential factor on the participants' results. Fig. 16 shows how the more experience with robots the user had, the higher they scored the gesture control. Due to the low sample size of expert users no definite conclusion can be drawn from this but one explanation could be that expert users are more likely to have used alternative methods of robot control in the past, such as haptic, voice or even other gesture systems. This is supported by those with "some" experience giving the RTP the highest scores of all users, as this is the method of control they are most likely to have previously used. However, this doesn't account for the users with no experience ranking the RTP higher, though this too can perhaps be explained by experience, not with robots but with the methods of interface themselves. Thanks to smartphones and tablets, almost everyone is now deeply familiar with touchscreen control. On the other hand, many participants expressed that this was their first time ever using a gesture control system, which would further increase the pressure for those that also had no robot experience. An additional factor contributing to this pressure would be the manner of errors encountered by the participants. It is already known that malfunctions in robotic systems can severely damage user trust (Honig and Oron-Gilad, 2018). With the RTP, the most common error was the touchscreen failing to register the participant's finger when pressing the screen which meant the robot did not move. In comparison, errors with the gesture system commonly related to hand movements that were accidentally made in the Leapmotion's envelope or occlusion of the participant's hand with their own arm during operation. These led to the robot moving unexpectedly, which would understandably be more alarming.

All participants took less than a minute to practice with either system despite being given up to 10 minten minutes, which is a testament to the simplicity of both systems, but several expressed regret that they had not practiced longer with the gesture control as they only began to feel comfortable with it towards the conclusion of the task. This makes sense when considering the gesture control requires dexterity and a level of muscle-memory to feel natural, as opposed to simply pressing on a screen. Verbal feedback from participants helped to identify improvements for the system to assist with this, as some desired the ability to swap the functionality of the left and right hands, allowing them to control motion with their dominant left hand instead. Others requested the ability to invert the controls, an option that is typically provided for joysticks in video games as it feels more natural to some.

Most of what has been covered in the analysis of the usability scores would also apply to the additional time taken to complete the task with the gesture control that was shown in Fig. 15. An additional consideration here is the slower movement speed used by the commands sent by the gesture system. The speed was kept deliberately low to try and increase the comfort of the participants, but in comparison many participants never moved the RTP's speed slider below 100% and some expressed that they wished the gesture system could move the robot faster.

It is important to remember the inherent advantages the gesture system has over the RTP and some other methods of control. The system doesn't require a large number of different buttons and controls that either take up physical space or space on a screen. The Leapmotion itself

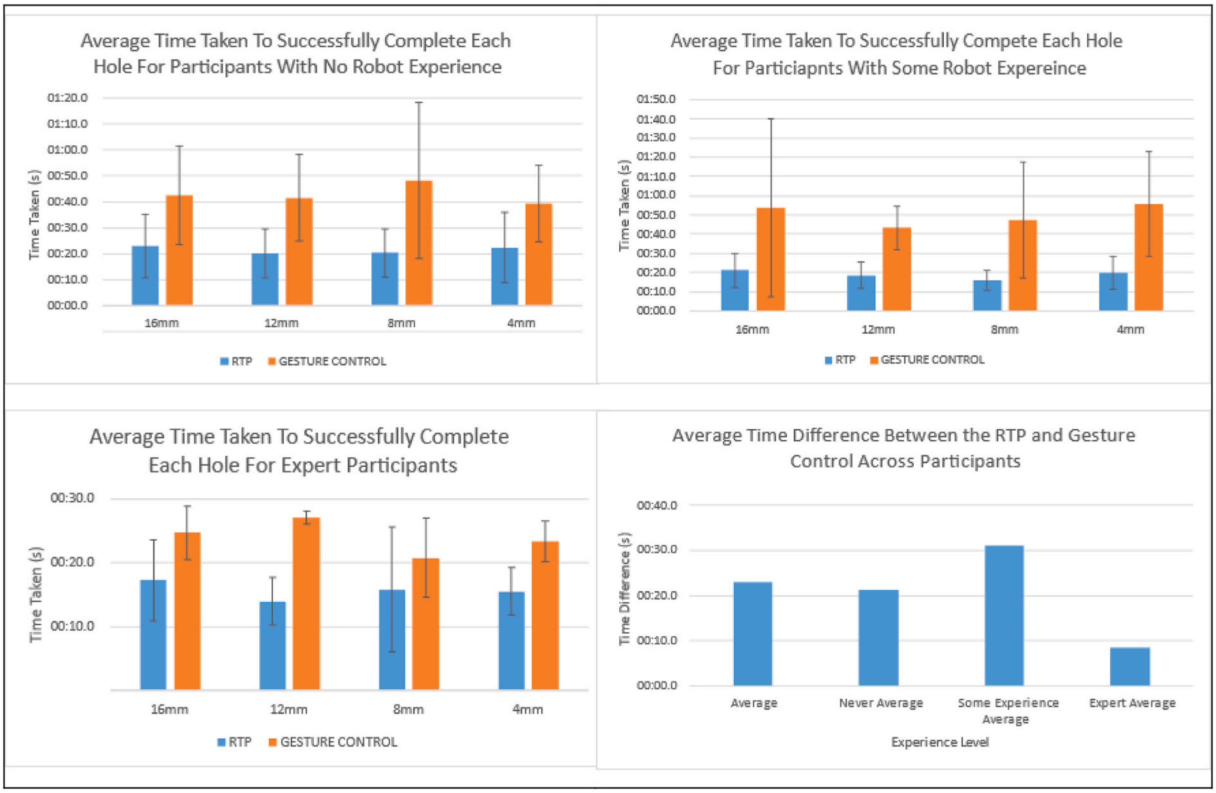


**Fig. 16.** Graphs displaying the timing results for participants with no experience (top left), some experience (top right), experts (bottom left) and the average increase in time taken to complete the task with the gesture system (bottom right).

is a quarter of the size of a modern smartphone making it easily portable and useable with any computer that has the appropriate software. It can easily be repositioned for each user to ensure it maintains its ergonomic advantage. Unlike the RTP and wearable gesture devices it is completely contactless, limiting risks of spreading contamination or illnesses and requires no adjustment for different hand-sizes. Background noise will not interfere as it would for voice control, and the inclusion of a GUI works to provide visual feedback and assist the operator with learning the controls and getting accustomed to the movement thresholds. By combining the mimicry and pre-set gesture approaches to arrive at the 3D joystick simulation, the weaknesses of both approaches have been eliminated.

Finally the limitations of both the system and study should also be considered. The hardware involved in the gesture system, specifically the Leapmotion, is far less reliable than the RTP's touch screen. Its operation is very dependent on external conditions and the quality of its calibration, where occlusion and shadows can reduce its ability to recognise the user's hands. Also the Leapmotion is constantly collecting data from within its working envelope while the program is running, meaning it is easier for unintentional commands to be sent to the robot if the user moves their hand within its range than with the RTP. Additionally, while gestures may be commonly used in tandem with speech as a means of communication, this is often an unconscious act. The frequent use of these gestures in day to day life did not seem to assist users when it came to the gesture system, which requires far more conscious and structured movements. In regards to the study itself, the limited number of expert participants resulted in an unfortunate lack of information for this experience level. Additionally, collecting data about previous use of gesture systems may have helped to explain the high standard deviation between those users. Even if it was not for controlling a robot, if a participant had previous played with a Microsoft Kinect or something similar before, this could have better prepared them for using the Leapmotion.

## 5. Conclusions

This paper has presented a novel gesture control system that aimed to avoid the shortcomings of other gesture systems while providing an ergonomic and easy-to-learn method of robot control and basic programming. The system successfully avoided the limitations recognised in other approaches and was designed to have as low a risk as possible of musculoskeletal injury, with its very low RULA score reflecting this. Operators that had never used a robot nor gesture control system before were able to successfully carry out a simple task with no training and less typically less than a minute practice time. While the experiment still gave the system a favourable score for usability, the gesture system was outperformed by the UR3's RTP meaning there is room for future work. This work would focus on improving the usability score through the inclusion of some of the suggested improvements, such as the ability to invert the controls or swap the dominant hand. The Leapmotion itself was released in 2012, so future improvements in hand tracking technology may help to reduce the chance of errors that led to reduction in trust. Additionally, it would be interesting to explore the significance of including the GUI and the inclusion of tactile feedback through ultrasonic emitters, or improved 3D visual feedback using augmented reality, could further improve the system.

## CRediT author statement

Conceptualisation – Sam Bordoni and Dr Gilbert Tang.

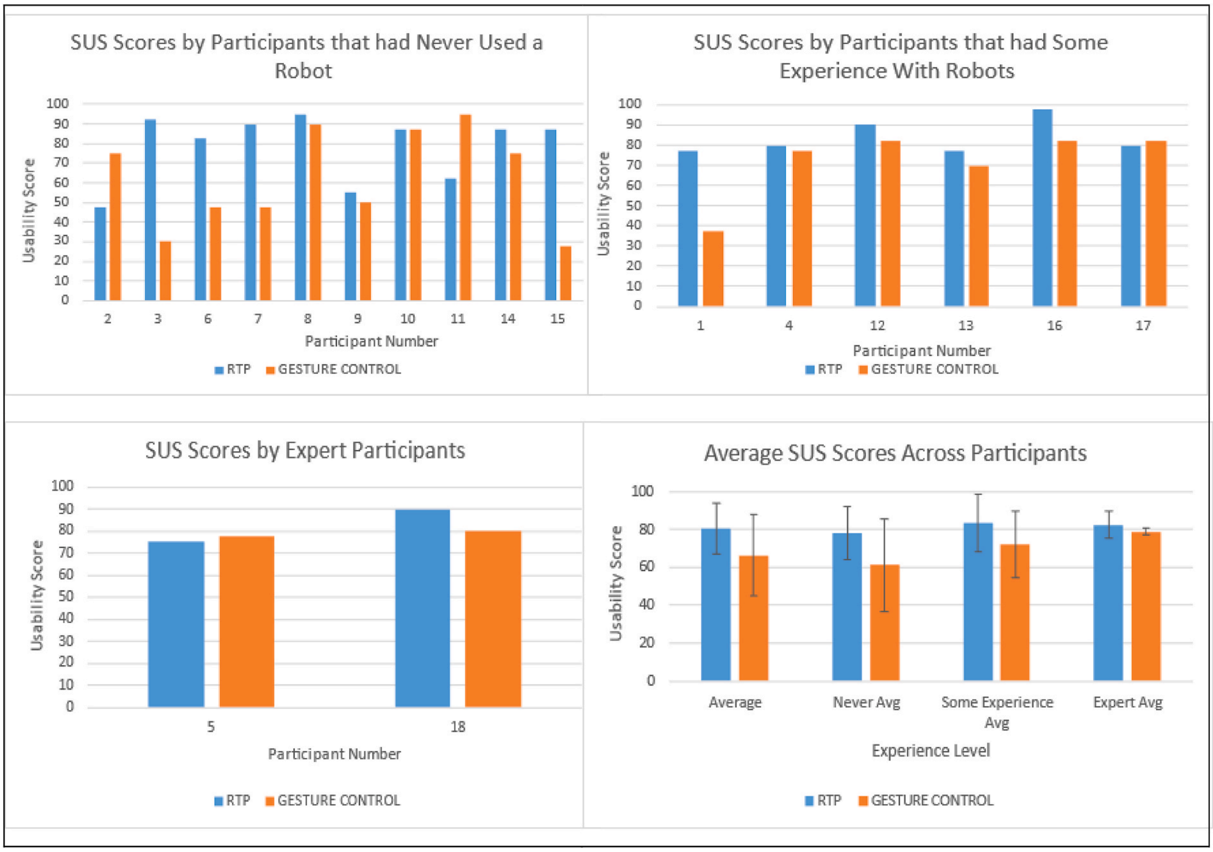


**Fig. 17.** Graphs displaying the SUS results for participants with no experience (top left), some experience (top right), experts (bottom left) and the average scores across all participants (bottom right).

Methodology – Sam Bordoni and Dr Gilbert Tang.
Software – Sam Bordoni.
Investigation – Sam Bordoni.
Project administration – Sam Bordoni and Dr Gilbert Tang.
Resources – Sam Bordoni and Dr Gilbert Tang.
Supervision – Dr Gilbert Tang.
Writing – original draft – Sam Bordoni.
Writing – review and editing – Dr Gilbert Tang.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Appendices.

### *Appendix A*

Participant Number:
Age:
Gender:
Dominant Hand:
Right/Left/Ambidextrous.
How much experience do you have with robots?
I've never used a robot/Some previous experience/Expert.

### *Appendix B*

Give first questionnaire.
Explain some basics about the manipulator:

- So, this is what we call a six degree of freedom collaborative manipulator. The collaborative term refers to the fact that it is safe to work in proximity to humans without extreme safety measure, hence why we have no cage around it.
- There are six individual joints that make up the robot, you can think of joints 1 and 2 being similar to your shoulder, joint 3 is like your elbow, and then 4 5 and 6 are like your wrist.

- There are two main ways to control this robot, one is using cartesian control on the X Y and Z axes, and the other is joint control by changing the angle of individual joints.
- Cartesian motion is useful for most movements as it directly controls the position of the gripper. However, it always tries to move in a straight line without changing the orientation of the gripper, so it can be a bit limited.
- This is where joint control is useful, as it gives you a higher level of control over the robot and can get the arm out of awkward positions or avoid them all together.
- Any questions about the robot?

Explain the required task:

- So, the task I'll be getting you to do is to compare these two different methods for controlling the arm.
- We have a pipe here, and then four holes that get progressively smaller.
- Starting from this position each time, your task will be to use the robot to insert the pipe into each hole, starting with the easiest.
- You will be allowed three attempts per hole, and the conditions for failure include touching the top surface of the rack, causing the robot to enter a protective stop or shutdown state, moving the rack, dropping the pipe into an unrecoverable position or if you ask to reset.
- I will be timing each hole but its not a race, so its more important to work accurately and at a speed you are comfortable with.
- You're mostly going to want to use cartesian motion, but feel free to use any of the other movements as you see fit.
- Once you've completed the task, I'll give you a short questionnaire to fill out just asking about the experience with the two systems.
- Any questions about the task?

Begin first system demonstration:

- Explain how to move in X Y and Z.
- Explain how to rotate around X Y and Z.
- Explain how to alter the joint angles.
- Any questions about the system?
- Allow participant some time to practice, then do task.

Do the same for the second system.

## *Appendix C*

Participant number:
Which system did you just use?
Touchscreen/Gesture Control.

| | | |
|---|---|---|
| I think that I would like to use this system frequently when controlling robots. | | |
| Strongly disagree | 1/2/3/4/5 | Strongly agree |
| I found the system unnecessarily complex. | | |
| Strongly disagree | 1/2/3/4/5 | Strongly agree |
| I thought the system was easy to use. | | |
| Strongly disagree | 1/2/3/4/5 | Strongly agree |
| I think I would need the support of a technical person to be able to use this system. | | |
| Strongly disagree | 1/2/3/4/5 | Strongly agree |
| I found the various functions in this system were well integrated. | | |
| Strongly disagree | 1/2/3/4/5 | Strongly agree |
| I thought that there was too much inconsistency in the system. | | |
| Strongly disagree | 1/2/3/4/5 | Strongly agree |
| I would imagine most people would learn to use this system very quickly | | |
| Strongly disagree | 1/2/3/4/5 | Strongly agree |
| I found the system to be very cumbersome to use. | | |
| Strongly disagree | 1/2/3/4/5 | Strongly agree |
| I felt very confident using the system. | | |
| Strongly disagree | 1/2/3/4/5 | Strongly agree |
| I needed to learn a lot of things before I could get going with the system. | | |
| Strongly disagree | 1/2/3/4/5 | Strongly agree |

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