

# An Interface for Remote Robotic Manipulator Control That Reduces Task Load and Fatigue

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**Abstract**— Remote control robots are being found in an increasing number of application domains, including search and rescue, exploration, and reconnaissance. There is a large body of HRI research that investigates interface design for remote navigation, control, and sensor monitoring, while aiming for interface enhancements that benefit the remote operator such as improving ease of use, reducing operator mental load, and maximizing awareness of a robot’s state and remote environment. Even though many remote control robots have multi-degree-of-freedom robotic manipulator arms for interacting with the environment, there is only limited research into easy-to-use remote control interfaces for such manipulators, and many commercial robotic products are still using simplistic interface technologies such as keypads or gamepads with arbitrary mappings to arm morphology.

In this paper, we present an original interface for the remote control of a multi-degree of freedom robotic arm. We conducted a controlled experiment to compare our interface to an existing commercial keypad interface and detail our results that indicate our interface was easier to use, required less cognitive task load, and enabled people to complete tasks more quickly.

## I. INTRODUCTION

Remotely controlling robots is a challenging task which places high demands on an operator’s attention, requiring them to maintain awareness of both the remote robot’s state and its operating environment while issuing precise commands. The complexity of this task and the importance of having clear, easy-to-use interfaces that do not overload operators is evidenced by the critical domains where robots are emerging, including urban search and rescue, extreme exploration (space, deep-sea, volcanoes, etc.), remote surgery, and high-cost industrial inspections (e.g., with nuclear reactors) [1–4]. For designing robotic control interfaces it is not sufficient to simply focus on providing detailed and complete control capability; ease of use should always be an integral priority. Many use cases require only sporadic robot use (e.g., search and rescue) and thus interfaces cannot always rely on extensive training and operator expertise. Even when expertise is assumed, interface designs should still aim to lower cognitive demands and workload, thus reducing stress, fatigue and error rates, and improving safety and operator health [5]. Balancing ease of use with extensive interface functionality is nontrivial.

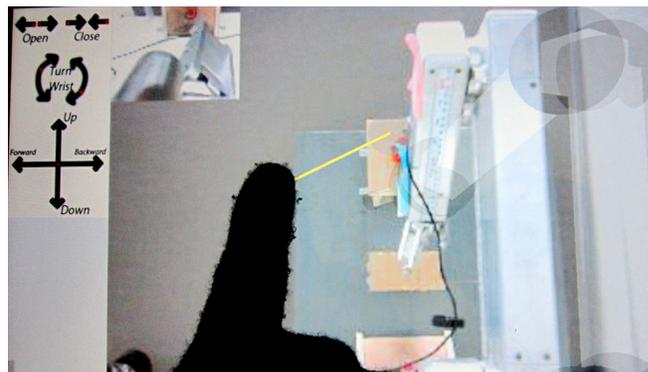


Figure 1. A user remotely operates a four degree-of-freedom robotic arm using our touch screen interface.

A goal in Human-Robot Interaction (HRI) research has been to design robot control interfaces to maximize operation effectiveness and efficiency while minimizing operator cognitive load, for example, by improving operator awareness of the robot’s state and the remote environment [6]. This research, however, has not explicitly focused on designing for multi-degree-of-freedom arm manipulators for interacting with a remote environment, despite the prevalence of robots with these types of controls.

In this paper we present the design, implementation and evaluation of a new interface (Figure 1) that aims to improve the ease of remote controlling a multi-degree-of-freedom robotic manipulator arm. In our design we give particular consideration to in-the-field use scenarios (e.g., urban search and rescue), where operator constraints may exist such as wearing bulky gloves, needing to be mobile, etc. We compared our new interface against an existing industry product via a formal study, testing difficult remote manipulation tasks (e.g., flipping a small switch), and show how our design reduced overall effort, physical demand, and frustration, while improving task completion speed, in comparison to the industry interface.

## II. RELATED WORK

Interface design for remote robotics has primarily focused on high-level whole-robot monitoring and control, for example, investigating how to integrate large amounts of sensor data (camera feed, battery level, motor loads, sonar, etc.) into control interfaces in ways that are easy to comprehend and use in real time [7–9]. A recent theme in this vein has been the investigation of how multi-touch screens and surfaces can be applied to remote robotic control, for example, a Photoshop-style sketch interface for defining robotic tasks and routes in a domestic environment [10], or a multi-touch gesture interface for robot walking [11]. Other lightweight

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interaction techniques for controlling robotic arms include using gestures (freehanded [16] or with a wand, e.g., a space mouse [17]), although so far such approaches have been found to be somewhat difficult to learn and cumbersome [16, 17]. We continue this trend by investigating ways to improve control-interface design for remote robotic manipulator arms.

Specifically for manipulator control, traditional joysticks have been popular as a familiar input device with a clear control scheme (e.g., [12]). The interface design challenge remains of understanding how joystick axes can be mapped effectively to manipulator capabilities, and how the joystick's few degrees of freedom (DOF), typically two to three, can be used for manipulators with (sometimes many) more DOF. As a type of custom manipulator-specific joystick, some use a replica of the manipulator or device being controlled (such as with [12]), where operators handle the tangible replica as if it was the actual remote manipulator. The benefits of such absolute-position interfaces are clear, as the control model matches the device being operated, and setting a target configuration can be achieved simply by moving the replica [13]. Similarly, an emerging body of tangible user interfaces for robotic [15] and manipulator [14] control looks to leverage people's innate spatial abilities to improve ease of interface use. Some even employ haptic feedback to help the operator maintain awareness of how the manipulator is interacting with the environment [1,18]. One drawback is that such devices are bulky and require space – replicas must have room to perform the full range of possible manipulator movement – and thus may limit flexibility of usage scenarios in the field. It could also be difficult to isolate commands; to operate one joint without modifying others. Their mechanical complexity also makes replicas comparatively expensive and difficult to produce. Thus, while tangible replica controllers have clear advantages, we believe that it is important to investigate alternate interface design approaches that mitigate some of these drawbacks, for example, to offer more lightweight interaction and to be more flexible for in the field use.

There are few other user-centered interface approaches for the remote control of robotic manipulators. A mixed reality interface enables operators to grab and move a robot or manipulator by touching and dragging small handles for fine-tuned motions [19]. For gloved, mobile operators in the field such fine-detailed movements may be difficult, and we believe that it is important to look to coarser-grained interaction. The area of brain-controlled interfaces uses techniques such as EEG to enable operators to control manipulators directly through thought [20], although this direction is still in its infancy and the development of interface techniques using current technology is still needed.

Our work presented in this paper provides a lightweight, easy-to-use remote manipulator interface that is appropriate for the various challenges faced with in-the-field operation, and we provide a formal controlled study that compares this new interface to an existing industry product.

### III. INTERFACE DESIGN

In this section we detail our interface design and implementation for the remote control of a specific robotic manipulator arm.

#### A. 4-Degree-of-Freedom (DOF) Manipulator

We used an Inuktun VT450 four DOF manipulator arm which has two planar one DOF joints to move forward, backward, up, and down, and a two DOF gripper which can open, close, and rotate in either direction (Figure 2). Note that this manipulator cannot move out of the plane. The manipulator further has a camera embedded in the gripper for end-point viewing, and when connected to the Inuktun Versatrax 450 Robot, there is a behind-arm camera.

#### B. Interaction Design Approach

Our overarching design goals were to develop a remote control interface that focuses on ease of use while maintaining powerful and precise control capability and emphasizing in-the-field usage scenarios.

One component of our interface design was to integrate the input and feedback spaces as closely as possible, to improve ease of operation [21]. For this purpose we adapted a multi-touch screen for control, to enable operators to interact directly using touch on the remote video feed (Figure 1); this eliminates the user's need to "context switch" between the input and output, and follows work in mixed reality that enabled people to interact with the real world through a graphical display (i.e., using a mouse to turn a remote knob on a live video feed [22]). We integrated both camera feeds into the single display using a picture-in-picture technique.

Another focal point of our interface design was to create a clear spatial mapping between command input and manipulator movement; to build a meaningful link between the physical and spatial actions performed by the operator and the corresponding manipulator movement. First, we designed the interaction around the idea of end-point manipulation [23] instead of specific joint manipulation (Figure 2) where operator commands are in terms of how they want the manipulator gripper to move, not each individual joint. We believe that this end-point approach matches typical manipulator tasks (e.g., picking up or pressing something) more than specific joint control. Further, we designed our touch screen gestures themselves to reflect how the actual manipulator moves, for example, upward and downward

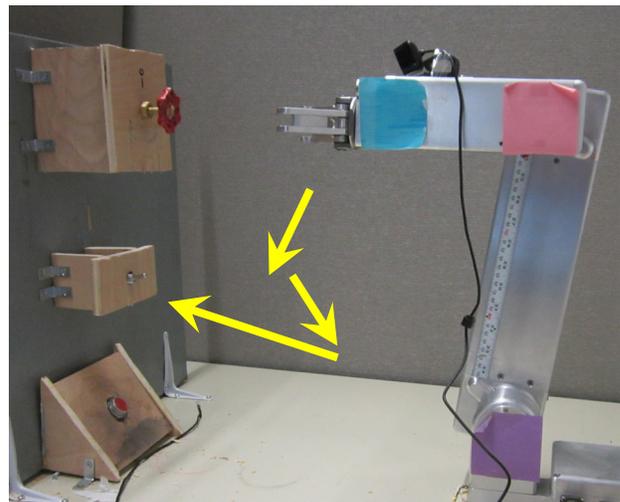


Figure 2. The 4 degree-of-freedom manipulator used: it has two planar joints and a gripper that rotates, opens and closes. The arrows indicate the end-point manipulation mental model, where users consider movements in terms of where the gripper should go, not the individual joints.

movements on the screen correspond to the manipulator moving up or down. Good spatial mapping lowers the need for operators to mentally translate commands to output movement, aiding the development of accurate mental models and lowering the cognitive effort required [21].

We integrated accurate state feedback of the current manipulator configuration into the interface to improve the operator’s awareness of the robotic state, reducing required mental effort and operator error rates [6].

### C. Interface Mechanics

Our control interface (Figure 3) integrates both camera feeds into one touch screen view. The user can switch between the camera views by simply tapping the smaller thumbnail, which initiates a quick transition. In addition, the view screen contains a ghost graphical image of the current arm configuration, to provide constant feedback to the user.

The basic interaction paradigm of our interface is: the operator touches the screen and drags in a direction to indicate manipulator movement. When the first touch is detected, a disc is drawn under the touch to serve as a visual anchor for the gesture’s starting point. As the operator moves their touch, a line is drawn between starting point and the current touch to indicate the direction of the movement command. Up and down correspond to the manipulator moving up and down in the real world, and left and right correspond to the manipulator moving forward and backward (Figure 4), to match the side-angle view of the feedback indicator. An angle movement indicates a simultaneous up-down and forward-backward movement. To operate the gripper, two-touch motions are used. A pinch in or pinch out is used to close or open the gripper, and a clockwise or counter-clockwise twist moves the gripper accordingly. These gestures can be combined, for example, to simultaneously open and twist. These gestures match the remote physical manipulator movement directly and are reflected on the interface as a legend (Figure 1).

Fine-detailed control is possible even when an operator has limited dexterity, for example, when wearing bulky gloves. The speed of the motion is determined by the length of the movement line, such that even coarse touch ability can correspond to slow manipulator movements, yet high speed is possible with larger line distances. When the touch is lifted all movement is stopped.

This relative-position interface (in contrast to absolute position) enables a person to control the manipulator based on desired movements such as “move forward, twist clockwise” instead of forcing them to consider the end target configuration. For example, a user can move toward a target just by doing a “forward” command irrespective of the global arm configuration. Further, this enables a measure of safety where operators can simply release their touches to stop motion, and then re-consider their next command.

### D. Implementation

We used an Android tablet (Toshiba AT330) as our input device. This tablet communicated with a laptop (Toshiba Tecra R700) which controlled the manipulator arm and collected video streams; commands, video, and manipulator state information was sent between the two using 802.11n wireless. Arm control was achieved over RS-485, and for the



Figure 3. The interface has two camera feeds, the main view and a thumbnail view (top-right corner). Switch between the two views by tapping on the thumb nail. The ghost image (bottom-left) indicates the robotic arm’s current configuration.

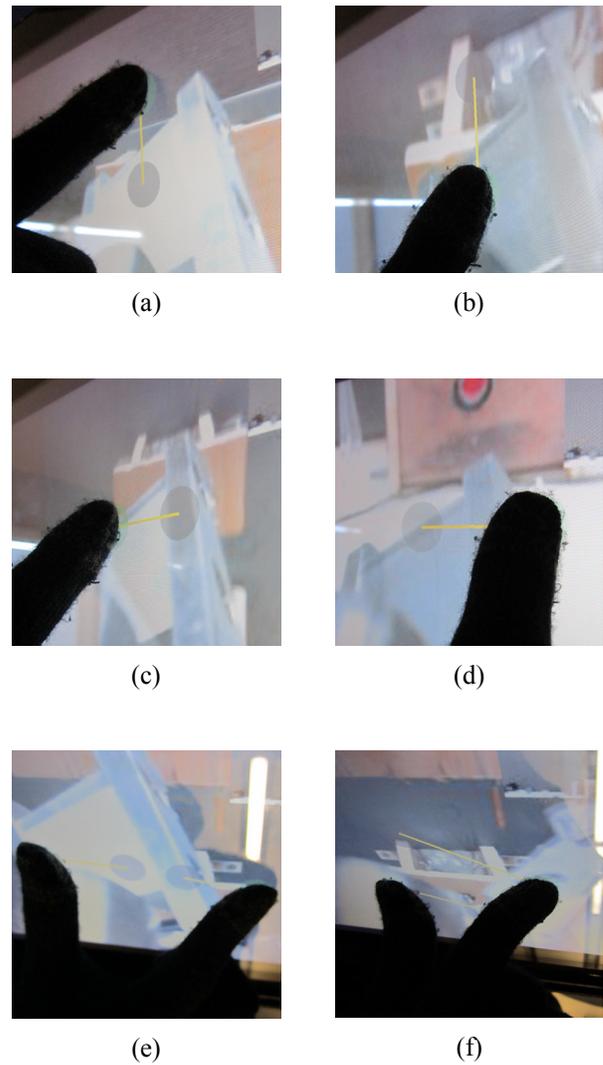


Figure 4. The various gestures. (a),(b) to move the arm endpoint up and down, (c),(d), to move the arm forward and backward, (e) pinch / unpinch to close / open the gripper, and (f) rotate two fingers to rotate the gripper

video feeds we used two web cameras, one attached to the robot arm and one behind the arm.

The robot arm does not provide the current position of its joints. Therefore, to record the position of the arm, we implemented rudimentary computer vision which tracked the arm configuration via colored markers (Figure 5) to be sent to the tablet for visualization.

Finally, we implemented an inverse kinematics solver to enable end-point operation, where relative movement commands (e.g., move up) are combined with the current state and solved for a new arm configuration.

#### IV. STUDY

We conducted a study to compare our new interface design with an existing industry product. The goals for our study were to focus on evaluating operator workload and task efficiency.

##### A. Existing Industry Product

We compared our new interface design against an Inuktun Versatrax 450 four DOF manipulator arm controller, the interface built for and packaged with our manipulator arm (Figure 6). Control is achieved through a keypad interface, with eight buttons for manipulator movements: for each joint there are two buttons, one per direction. For example, the rightmost two buttons control the opening and closing of the gripper. The interface provides the two live camera feeds using two monitors side by side (Figure 6).

At this point we highlight that this interface does not meet the design criteria integrated into our new interface: the spatial mapping between button layout and manipulator movements is somewhat arbitrary, requiring an operator to mentally search the buttons for desired functionality and map an action to expected output. Such arbitrary mapping can be expected to hinder memory and training, where operators may take much longer to learn the interface [24]. Further, the output is spatially disjoint from the input; the screens are far from the keypad. As we expect the keypad to be somewhat difficult to use, this will likely require constant operator-focus shifts between the keypad, to give a command, and the output screens, to observe the results. We expect this “context switching” to decrease interaction effectiveness. Finally, the industry interface does not provide any feedback of the manipulator’s current configuration, forcing an operator to maintain a detailed mental guess. Overall, we hypothesize that these issues will result in our new interface requiring less cognitive load and thus will make it more efficient than the existing industry interface.



Figure 6. Arm tracking using simple computer vision, required to provide current-configuration state feedback to the user

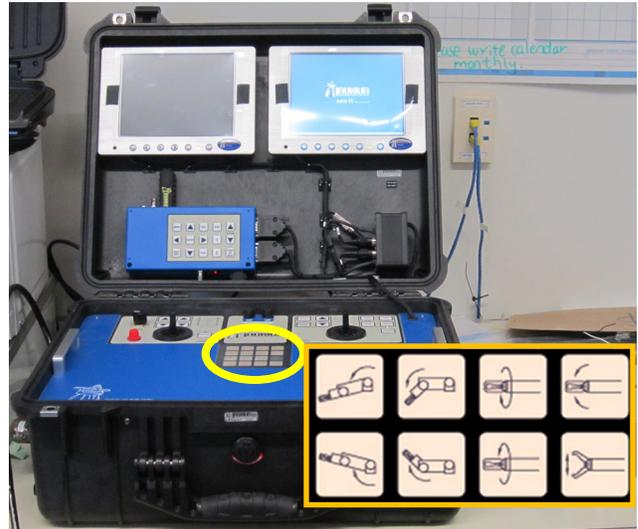


Figure 5. Industry controller and interface (Inuktun Versatrax 450).

##### B. Study Design and Tasks

Participants performed three tasks that we developed to be challenging and to require fine control of the robot manipulator: turning a faucet (first clockwise 360 degrees and then counter-clockwise), pressing and releasing a small button, and flipping a small toggle switch in both directions. Component layout is shown in Figure 7.

###### 1) Evaluation Instruments

To evaluate operator workload we employed NASA’s Task Load Index (TLX) [5] self-report questionnaire, a standardized instrument for measuring workload across six

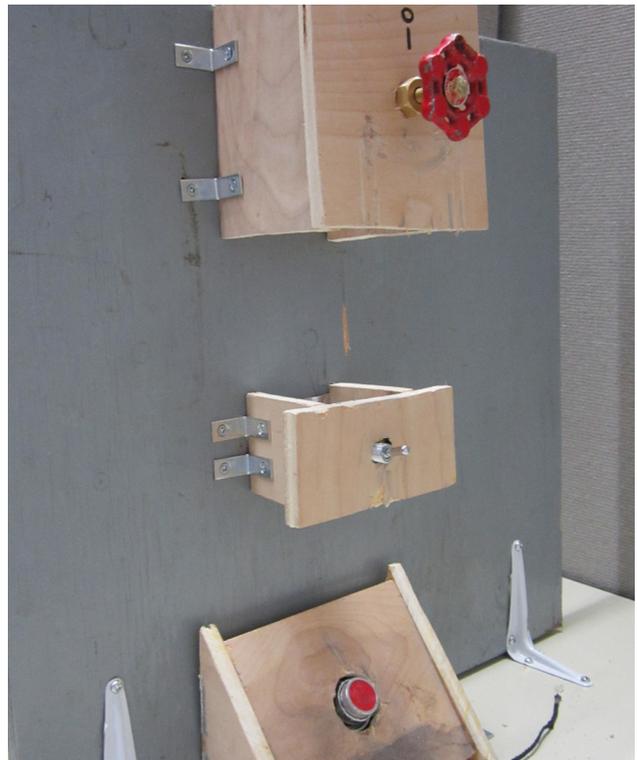


Figure 7. The three tasks: turning a faucet – a full turn in both directions, flipping a toggle switch on and off, and pressing a button.

scales: to rate mental demand, physical demand, temporal demand (how hurried or rushed one felt), effort (how hard one had to work), performance (self-assessment of task success) and frustration. In addition, we administered a post-study questionnaire to elicit overall and general interaction experience, preferences, and interface suggestions.

## 2) Methodology

We recruited 20 participants from our general university population (aged 19-41, 15 male, 4 female) for the 60 minute study. The protocol was approved by our university research ethics board and participants received a \$10 cash honorarium for their participation.

Participants were given a brief overview of the study and an introduction to the robotic arm: we described how it moves and introduced the tasks they will be doing. Next we administered an informed consent form and a demographic questionnaire, and awarded the honorarium.

We employed a within-subjects design where all participants completed all tasks with both our new interface and the keypad interface. The order of interface use was counterbalanced between participants. The task order was kept constant as we had no inter-task variable that was being tested.

To simulate remote interaction, tasks were completed in an isolated cubby area where participants could not see the actual manipulator except through the video feeds. Although the manipulator was on the opposite end of the room, participants also wore headphones playing soft white noise to avoid them hearing any manipulator movements.

Before starting the tasks with a specified interface, participants were given a 5 minute tutorial of the control scheme. Participants then proceeded to wear work gloves and completed an experimenter-assisted trial run, in which they put the arm in different configurations (e.g., completely straight, folded down), to ensure understanding of the interface. After completing all tasks with an interface we recorded the completion time and administered a NASA-TLX sheet, and the participant continued to the next interface. At the end of the experiment participants filled-in the post-study questionnaire.

## C. Results

We conducted one-tailed paired t-tests on task completion time and all dimensions of the NASA-TLX scale to test our hypotheses of our new interface being more effective and requiring less mental demand than the keypad interface.

On average, participants were 17% faster (87.8s) with our new interface ( $M=406.93$ ,  $SE=34.625$ ) than the keypad interface ( $M=494.73s$ ,  $SE=39.579$ ),  $t(14)=-2.447$ ,  $p<.05$ ,  $r=.55$ . In terms of workload, participants experienced less physical demand with our new interface ( $M=8.47$ ,  $SE=1.41$ ) than the keypad interface ( $M=11.6$ ,  $SE=1.74$ ),  $t(14)=-1.958$ ,  $p<.05$ ,  $r=.46$ . Participants reported that less effort was required with our new interface ( $M=8.07$ ,  $SE=1.482$ ) than the keypad interface ( $M=12.4$ ,  $SE=1.35$ ),  $t(14)=-2.045$ ,  $p<.05$ ,  $r=.48$ , and that they experienced less frustration<sup>1</sup> with our new interface ( $Mdn=5.0$ ),  $z=-1.475$  than the keypad interface ( $Mdn=11.0$ ),

$p<.1$   $r=-.38$ . No significant differences were observed for reported mental demand, temporal demand, or performance.

In the post-study questionnaire 73% of participants reported that they preferred using the touch interface. Reasons cited include it providing a “clearer view of the configuration of the arm with the overlaid image” and that it “takes little force.” Negative feedback includes comments such as “visual feedback is less explicit than haptic feedback” (i.e., feeling the physical buttons) or that they “can't see both cameras at once,” where they could with the industrial interface.

## D. Discussion

The results from our experiment reveal that our new interface was successful in improving task efficiency and reducing operator cognitive workload in comparison to the industry interface. Participants completed remote operation tasks more efficiently using our new interface and rated it as having lower physical demand, requiring less effort, and being less frustrating than the keypad condition. Participants also preferred our new interface to the existing one.

We believe that these improvements in performance, perceived workload and preference are directly attributable to our design approach of integrating input and output spaces, improving the spatial mapping of the interface, and providing clear state feedback of the manipulator. Our results show that our novel applications of established HCI design principles can improve the ease-of-use and efficiency of remote-control robotics interfaces for in-the-field control.

## V. LIMITATIONS AND FUTURE WORK

This project was only a first step in exploring how interfaces for multi-degree-of-freedom manipulators could be improved using HCI design methodology. Moving forward we intend to conduct further controlled studies to isolate the relative benefits of the principles used to guide the design of our manipulator interface. Further, we will expand our exploration to manipulators with higher DOF and complexity (e.g., allowing the manipulator to move left-right as well as forward-backward), as well as how a manipulator interface could be integrated into a full-robot control scheme including, for example, robot locomotion control.

## VI. CONCLUSIONS

In this paper we presented the design and implementation of a new interface for easy-to-use remote operation of a multi-degree-of-freedom robotic arm. By means of a controlled study we demonstrated how our interface was successful in improving ease of operator use as well as task efficiency in comparison to an existing interface. Overall, this project highlighted how new interface technologies such as multi-touch surfaces can be leveraged to lower operator cognitive load and increase task efficiency.

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<sup>1</sup> Wilcoxon signed-rank test was used as data was not normal

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