RESEARCH-ARTICLE

Embodied Expressive Gestures in Telerobots: A Tale of Two Users

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Despite their technical advancements, commercially available telerobots are limited in social interaction capabilities for both pilot and local users, specifically in nonverbal communication. Our group hypothesizes that the introduction of expressive gesturing and tangible interaction capabilities (e.g., handshakes, fist bumps) will enhance telerobotic interactions and increase social connection between users. To investigate the affordances to social connection that gestures and tangible interactions provide in telerobot-mediated interactions, we designed and integrated a lightweight manipulator terminating in an anthropomorphic end effector onto a commercially available telerobot (Anybots QB 2.0). Through virtual reality tracking of the pilot user's arm and hand, expressive gestures and social contact interactions are recreated via the manipulator, enabling a pilot user and a local user to engage in a tangible exchange. To assess the usability and effectiveness of the gesturing system, we present evaluations from both the local and pilot user perspectives. First, we present a validation study to assess usability of the control system by the pilot user. Our results demonstrate that pilot user interactions can be replicated with a greater than 80% pass rate and mean ease of use rating of 7.08 ± 1.32 (out of 10) with brief training. Finally, we present a user study to assess the social impacts of (1) using the telerobot without the manipulator from both the pilot user and local user perspectives and (2) using the control system and telerobotic manipulator from both the pilot user and local user perspectives. Results demonstrate that the robot with the manipulator elicited a more positive social experience than the robot without the arm for local users but no significant difference in conditions for pilot users. Future work will focus on improving the pilot user experience to support social contact interactions.

CCS Concepts: • **Human-centered computing** → **Usability testing**; **User studies;**

Additional Key Words and Phrases: Telerobotics, social connection, human-robot interaction, tangible interactions, expressive gestures, robot design, mobile remote presence

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1 INTRODUCTION

Recent research on telepresence robots demonstrates that although such platforms are enabling new heights of remote communication, there still exist challenges for both the local users (those in contact with the telepresence platform) and pilot users (those controlling the platform remotely) in fostering the social connectedness that is intrinsically present in physical, face-to-face interactions [1, 13, 34, 39, 44]. A large part of our social experience is the ability to communicate and connect with one another beyond vision and hearing, including tangible interactions (e.g., hand shakes, fist bumps), expressive gestures, and referencing by pointing, which are three of the primary social behaviors relevant to human-robot interaction [26]. Tangible interactions, particularly handshakes, are highly prevalent in human culture [33]. Fist bumps, too, have become a culturally acceptable alternative to handshaking, as they reduce the transmission of germs [27]. Put simply—the ability to "talk with one's hands" is something humans do so eloquently in conversation that it enables them to connect and relate on a deeper level [17, 21]. Additionally, this nonverbal communication is critical to conveying core functions of communication, such as backchanneling, direction giving, turn taking, and attention getting [18, 23, 47]. Yet most commercially available telerobotic platforms do not possess expressive limbs, and so this intuitive, nonverbal communication is largely absent in the telepresence experience.

Our group hypothesizes that physical, tangible interactions and gesturing are necessary for supporting social connection in telerobotic communication. To this end, our initial work focused on the development of a lightweight manipulator integrated onto a commercial telerobotic platform, the Anybots QB 2.0 (Figure 1, left and middle) [22, 41]. We demonstrated that our initial manipulator design could achieve expected position and velocity profiles for expressive gestures (e.g., waving), tangible interactions (e.g., handshakes), and referential pointing within a defined workspace based on a human arm's range of motion. In this work, we expand upon these foundational efforts, introducing design enhancements to the local hardware (Section 2), implementation of the manipulator control system (Section 3), a validation study on usability (Section 4), and a two-part user study that investigates social connection between telerobot users (Section 5).

Specific contributions include an improved 5 **degree-of-freedom (DOF)** manipulator design and an updated commercially available hand, and an expanded field of view for both users, described in Section 2 and shown in Figure 1 (right). Using virtual reality tracking of the pilot user arm/hand poses and extending the FABRIK algorithm to replicate poses on the telerobot manipulator, we present the implementation of the manipulator control system in Section 3. In Section 4, we present a validation study assessing usability of the control system. In this validation study, pilot users performed a set of 14 gestures with the telerobotic manipulator and were asked to rate ease of use for each gesture. Finally, in Section 5, we present a two-part user study that investigates the social connection of both pilot and local users in a one-to-one exchange via the telerobot with and without the manipulator. The user study examines if and how the control system with the manipulator enhances social interactions from both the pilot user and local user perspectives. Taken together, this work expands upon previous results reported in literature in telerobotics, informing if and how gesturing capabilities enhance the telepresence experience for both local and pilot users. This work also presents the opportunities and limitations of enabling social, contact and non-contact gestures mediated through telerobotic platforms more broadly, informing the

Fig. 1. The Anybots QB 2.0 (left), the platform modified with the initial manipulator (center) [41], and the current modified platform (right).

necessary hardware and software design to support embodied expressive gesturing in telerobot-mediated communication.

1.1 Background

We first review robotic systems designed specifically for nonverbal, physical (contact and non-contact) interaction and then detail current gaps in telerobotic communication, particularly with respect to the lack of expressive and tangible interactions.

Several robots equipped with arms and hands representative of those of humans exist, including Asimo [19], ARMAR-3 [6], Robonaut [25], iCub [28], and WE-4RII [29]. However, many of these have been designed for manipulation tasks, not necessarily for social connection, favoring mechanical complexity over anthropomorphism and human interaction. These manipulators are also often task and hardware specific, not being designed to be integrated onto existing systems, such as telerobotic platforms, which have unique design constraints [41]. The goal of our design is to balance anthropomorphism with mechanical complexity to provide a natural and realistic interactive experience for local users and a simple and intuitive control system for pilot users.

Telerobots have been shown to enhance social connectedness in remote communication by virtue of being a physical embodiment of the pilot user [37, 42, 43]. Moreover, the interpersonal closeness of a pilot user to local users significantly influences the pilot user's feeling of presence in the remote environment [16]. For example, Lee and Takayama [24] explored how a commercial telerobot in a working environment affected informal communication between local and pilot workers. The telerobot was found to enhance connections and communications for pilot workers, as well as giving them a physical presence lacking in traditional videoconferencing avenues. Similar results have been reported with telerobots in educational and domestic environments [2, 48, 49]. However, a limitation with current telerobotic platforms is the lack of interaction options afforded to the pilot user. At a large-scale academic conference, pilot users reported struggling with social interaction, primarily spatial awareness and the absence of body language [31]. We propose that the introduction of a manipulator will address the latter, enabling a facet of communication previously unavailable to pilot users.

It has been demonstrated that robots using gestures elicit increased likability and greater perceptions of anthropomorphism and influence greater information retention in human users [20, 38]. However, there is another component to consider when applying gestures to telerobots: the experience of the pilot user. Using an OhmniLabs Ohmni telerobot equipped with a 3-DOF manipulator constrained to 2D motion, Fitter et al. [15] examined user responses to three control methods: an onscreen slider, a physical dial, and a skeleton tracking system. Although no significant differences in presence across the three methods were reported, users of the skeleton tracking method reported feeling a greater connection to the remote environment and noted that the method was both easy and enjoyable to use, despite a greater physical demand than the other two methods. These responses indicate that there are aspects of the pilot user experience that warrant further investigation into similar control systems.

Although mediated social touch has been studied quite extensively, many of these prior studies have paid limited attention to social telepresence and many have focused on developing a device that is tailored for a particular haptic sensation [30]. A few studies, however, have observed the effects of touch on social telepresence, and it was shown that audio communication accompanied by a touch channel was superior to audio-only communication in producing social telepresence [30, 46]. Additionally, in the work of Nakanishi et al. [30], a robotic hand with a soft covering that could simulate human hand temperature was developed and augmented underneath a large screen mounted on a wall. The pilot user's hand established a virtual hand shake with local users. The findings demonstrate that the presence of the hand allowed for a closer connection between local and pilot users [30]. The MeBot [1] is another example of a semi-autonomous robotic avatar that is much smaller in scale and houses a mobile phone on the top of its platform. The platform consists of two small arm-like appendages and a mobile base. This robot was designed specifically for conveying nonverbal social communication such as posture, head movements, and hand gestures. Experimental results comparing use of the MeBot with and without these gestures and movements show that people felt more psychologically involved and more engaged in the interaction with their remote partners when they were embodied in a socially expressive way [1]. In our work, we build on this prior work by investigating enhancements to nonverbal, social communication specifically in telerobotics, for both local and pilot users, through social, tangible interactions.

2 LOCAL HARDWARE

The overall system involves both local user (Figure 1, right) and pilot user (see Figure 5) hardware. The local hardware consists of the modified telerobotic platform and the integrated manipulator. A local user standing next to the telerobot is able to interact with the pilot user through handshakes, high fives, fist bumps, and the like via the telerobot manipulator along with video conferencing through the telerobot. The pilot hardware consists of a host computer displaying the remote user interface, a Manus VR Prime I motion capture glove, and an HTC Vive System for tracking. The pilot user stands at a computer and wears a wrist tracker on their right wrist and a finger tracking glove on their right hand. Mounted infrared pulse stations in the room track wrist positions. The pilot user also holds a controller in the left hand, which is used to calibrate the position of their right shoulder. Using traditional keyboard inputs or clicking on screen arrows, the pilot user can navigate the telerobot throughout a remote location. When the pilot user wishes to engage in social interactions, the pilot user holds the activation switch on the controller in their left hand and moves their right arm. The control system captures this movement and replicates it with the manipulator in the local space. In this section, we detail the components of the local hardware, before detailing the control and remote user interface components in subsequent sections.

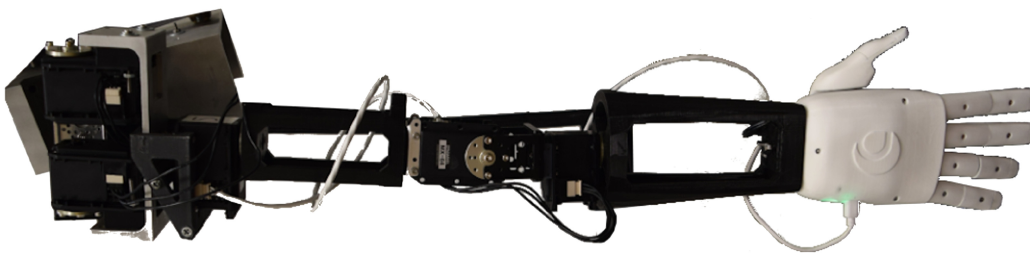

Fig. 2. The current manipulator design with the wrist motor, 3D-printed connectors, and Brunel Hand 2.0.

2.1 Telerobotic Platform

This work utilizes a commercial telerobotic platform, the Anybots QB 2.0 (Figure 1, left). QB is adjustable in height, has a small footprint, is capable of carrying up to 20 kg without compromising gyroscopic stability, and has customizable control software with remote access via a web browser. As shown in Figure 1, the original 137-mm video screen on QB was replaced with a Samsung 482.6-mm SF350 LED monitor to make the pilot user's face display size more proportional to the manipulator, and a higher-quality speaker (Elegiant SR100) was added to allow local volume control. A webcam on top of the monitor and a fisheye camera on the speaker provide views to the pilot user of the local space and of the arm, respectively. Additionally, a plate on the back of the monitor houses a fuse box and regulators for safe power distribution.

2.2 Manipulator

The first manipulator designed by our team was presented in the work of Feilner [41] and is shown in Figure 1 (center). This initial design was a 2.19-kg, 534-mm-long, 4-DOF arm with AL6061 connectors terminating with a five-fingered, 380-g Open Bionics Ada Hand. The DoFs included (1) shoulder flexion/extension, (2) shoulder abduction/adduction, (3) shoulder internal/external rotation, and (4) elbow flexion/extension. This design utilized six Dynamixel continuous DC servo motors with PID control and specifications provided in Table 1. The initial design was a proof-of-concept, so it did not include wrist pronation/supination, which limited the manipulator's ability to replicate certain gestures such as high fives, fist bumps, and waving. Further, its low fidelity, mechanical aesthetic had the potential to reduce the impact of social interactions [9]. To address these concerns, we redesigned the manipulator, depicted in Figure 1 (right) and Figure 2, in three areas. First, the AL6061 connectors were replaced with 3D printed black PLA connectors for a more anthropomorphic shape and a color that matches the Anybots QB 2.0 aesthetic. Second, the Open Bionics Ada Hand was replaced with the Brunel Hand 2.0, a newer hand from Open Bionics that employs a 12V, tendon-actuated, five-fingered design while utilizing a more anthropomorphic thumb shape, flexible palm material, reinforced finger joints, and reduced weight of 332 g (see Table 1). Third, a Dynamixel MX-28T motor weighing 72 g was added distal to the elbow to allow wrist pronation and supination. Adding this seventh motor converts the arm from 4-DOF to 5-DOF, which enables interactions and gestures such as high fives, fist bumps, thumbs down, waving, and handshake variations. The specification changes from these manipulator design updates are provided in Table 1. The weight of the whole arm increased from 2.19 to 3.11 kg, of which 1.49 kg is anchored to the neck of the telerobot and not part of the rotating mass. Despite the additional weight, the maximum torque experienced by the motors (during 90 degrees of shoulder abduction or 90 degrees of shoulder flexion) decreased slightly from 2.92 Nm on the initial design to 2.90 Nm on the current design. The max torque remained relatively constant despite the increase in the total weight of the manipulator because of the reduction in weight of the Brunel Hand 2.0 compared to the Ada Hand, which is the most distal component of the manipulator. Keeping most

Table 1. Specifications of Manipulator Components (Motors and Hands) for Comparison Between the Initial Manipulator Design and the Current Manipulator Design [8, 35, 36]

	Initial Design	**Current Design**
Degrees of Freedom	4	5
Arm Length	0.694m	0.606m
Shoulder Width	0.170m	0.138m
Total Weight	2.19kg	3.11kg
Hand Weight	0.380kg	0.332kg
Max Torque	2.92Nm	2.90Nm
Voltage Supply	12–14.8V	12–14.8V

of the weight of the manipulator close to the shoulder reduces the torque required by the motors. The max torque is well within the operating ranges of both the shoulder flexion and shoulder abduction motors, as these joints have two directly-coupled motors each. The updated manipulator presented here provides aesthetic enhancements to match the telerobot persona and an additional DOF to increase gesturing capabilities without significant weight and power trade-offs.

3 CONTROL SYSTEM

At the core of the telerobot system is the control system (Figure 3). The control system uses two modes of communication between the computer of the pilot user and the computer on the local telerobot platform: Janus WebRTC and OpenVPN. These communication systems facilitate video conferencing (Section 3.1), robotic control (Section 3.2), and manipulator control (Section 3.3).

3.1 Video Conferencing

Janus WebRTC is a general-purpose server with plugins available to provide media communication through a web browser [3]. In this work, Janus WebRTC is used to control video conferencing. A minimal user interface was developed on top of the *videoroom* plugin to route the **audio and video (AV)** streams to the appropriate devices.

There are five streams for video conferencing: (1) an audio stream and (2) video stream from the microphone and webcam on the pilot user computer, (3) an audio stream and (4) video stream from the microphone and webcam on the local platform, and (5) a video stream of the manipulator from the fisheye camera on the local platform. The streaming is visualized in Figure 3. To video conference, a web browser is opened by both the pilot and local user. One page of the browser, activated on the pilot user computer, transmits the local user AV streams while collecting the pilot user AV streams. Inversely, a second page of the browser, activated on the local telerobot platform, transmits the pilot user AV streams while collecting the local user AV streams.

Along with the two video streams from the robot being displayed on the pilot user's computer, a real-time simulation of the manipulator's movement is also displayed, as shown in Figure 4. The generation of this simulation is explained in Section 3.3. Users can rely on both the camera feed and the simulation for visual perception of the manipulator movement when controlling the robot.

3.2 Robotic Control

The robotic control communication is accomplished through OpenVPN, a virtual private network system built for secure point-to-point or site-to-site data transfer between computers for remote access [14]. The computer on the local platform is established as the host address, and pilot computers can connect to the host's server though individualized client configuration files. The data

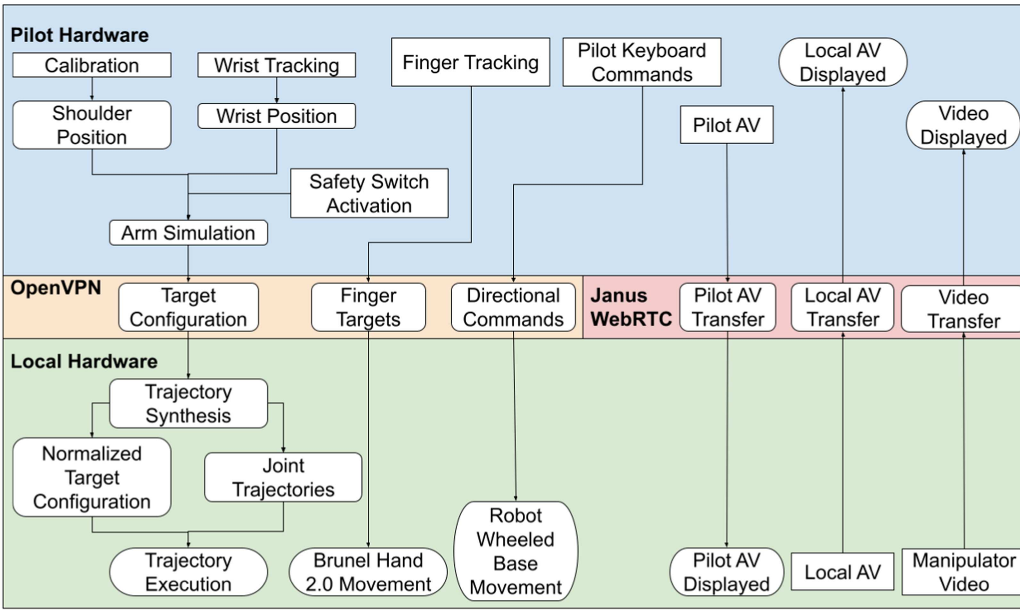

Fig. 3. The control system is spread across pilot (blue) and local (green) hardware. Its components consist of a Dynamixel motor, Brunel Hand 2.0, wheeled base, and video conferencing control with data transfer facilitated by OpenVPN (orange) and Janus WebRTC (red).

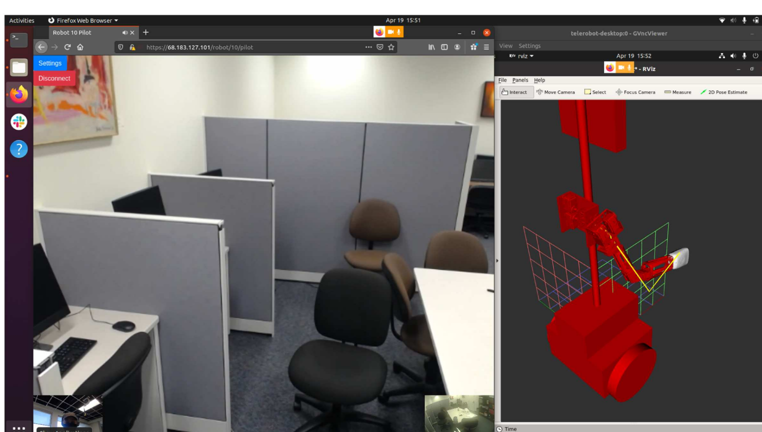

Fig. 4. The pilot user screen displays a camera feed from the robot (left), a graphical simulation of the manipulator (right), a fisheye camera feed of the manipulator (bottom center), and a self-view from the pilot user webcam (bottom left).

transferred through OpenVPN is compiled, processed, transmitted, and received by **Robot Operating System (ROS)** software bidirectionally between the server and local platform.

3.3 Manipulator Control for Expressive Gesturing

Our system also uses ROS and OpenVPN to control the actuation of the Brunel Hand 2.0, and the actuation of the manipulator joints by collecting, processing, and transferring data from the pilot control hardware. Finger tracking is achieved by the Manus VR Prime I motion capture glove [45] worn on the pilot user's right hand. Finger positions are recorded in degrees of flexion and sent to the local platform. Commercial software in the Brunel Hand 2.0 receives the finger flexion commands and translates them into corresponding motor positions for the linear actuators that control the artificial tendons.

The motion tracking hardware for capturing the pilot user's arm movement includes an HTC Vive infrared tracker [12] worn on the right wrist, an HTC Vive controller [11] held in the left hand, and two HTC Vive infrared pulse stations mounted at elevated positions in the pilot user's room. The control of the robotic arm is distributed across five components: calibration, wrist tracking, arm simulation, trajectory synthesis, and trajectory execution. The calibration, wrist tracking, and arm simulation is performed on the pilot user's computer while the trajectory synthesis and execution is performed on the local platform. The local computer within the Anybots QB 2.0 platform performs the majority of the arm control processing to ensure low latency communication and then it executes commands via the local hardware described in Section 2.

3.3.1 Calibration. The arm tracking requires a calibration step to set the initial position of the pilot's shoulder used to infer the pose of the arm during tracking. This calibration is accomplished by touching the anterior aspect of the pilot's shoulder with the HTC Vive controller and pressing a button. Upon calibration, the 6-DOF position of the handheld controller is recorded, and an offset is applied to estimate the location of the pilot's humeral head. The resulting shoulder position is saved as one end of the kinematic chain used to estimate the pilot's arm pose. The controller is also used as an activation switch to enable and disable the arm control. Manipulator movement is enabled only if the button on the grip of the controller is pressed, preventing unintentional motion and providing a remote emergency stop action.

3.3.2 Wrist Tracking. Wrist tracking involves the HTC Vive tracker worn on the wrist (Figure 5) and the mounted HTC Vive infrared pulse stations. The tracker detects the pulses from the mounted station and uses them to determine the absolute position and orientation of the pilot user's wrist. The wrist tracking component is intentionally kept minimal, consisting of a wrapper around the official OpenVR libraries published by Valve for interfacing with the HTC Vive.

3.3.3 Arm Simulation. The wrist and the shoulder positions and orientations are collected by ROS and used to simulate the configuration of the pilot user's arm. Arm simulation uses a FABRIK (Forward and Backward Reaching Inverse Kinematics) algorithm, an iterative inverse kinematics method that is well suited for modeling human movement [5]. Several modifications of the method have been implemented, as proposed in the work of Aristidou et al. [4]. The arm of the pilot is modeled as a 5-DOF chain, with the shoulder made up of three 1-degree joints in close proximity. FABRIK is used to generate a kinematic solution for the pilot's arm that is rooted at the initial position of the pilot's shoulder (as defined by the calibration routine described earlier) and matches the position and orientation of the pilot's wrist (tracked by the wrist-mounted tracker). The resulting kinematic solution is displayed with yellow lines on the pilot user's monitor (see Figure 4) representing the recorded position of the pilot's arm. It is then mapped to the robot's joints based on the distances between the motors (which differs from human anatomy specifically in the natural ball-and-socket joint of the shoulder). The joint angle targets are then sent through OpenVPN to the local platform computer to be converted for manipulator actuation execution.

3.3.4 Trajectory Synthesis. The local user system interfaces with the pilot user through the target joint configuration information updated as often as new target data is received from the pilot user's computer. During trajectory synthesis, the received joint targets are normalized as follows:

(1) Any target positions that are greater than 360 degrees away from the current position are updated to an equivalent position that is within 360 degrees.
(2) Any target positions that fall outside the maximum range of a joint are updated to be at the maximum range of the joint.
(3) If the arm is approaching full extension, coaxial joints are locked to their current positions to limit rapid movements caused by approaching a singularity.

After the target configuration is normalized, a straight line trajectory through joint space is generated from the current joint configuration to the updated target configuration. The velocity of the trajectory is set such that all joints arrive at the same time, and no joint violates the maximum velocity constraint of the motors. The joint trajectory goals sent through ROS for execution on the motors are incrementally updated to gradually move the arm toward its desired final position.

3.3.5 Trajectory Execution. The synthesized trajectory is sent to the trajectory execution component to be executed immediately on the manipulator. Any previously received trajectories are preempted with the most up-to-date trajectory. The trajectory execution also provides security in the event of communication loss. If no new goals have arrived within 500 ms, the trajectory execution system assumes that communication has been lost and returns the arm to a safe, neutral position, as shown in Figure 1. The execution of these trajectories is also a product of the **proportional, integral, and derivative (PID)** control implemented in each motor. The values of a motor's PID constants are dependent on the joint angle of which the motor is associated (e.g., both motors responsible for shoulder abduction have the same PID constants). The actual positions of the motors are recorded and sent back to the pilot user's computer through OpenVPN. These positions are translated to make a 3D simulation of the manipulator that is displayed on the pilot user's monitor (see Figure 4) to provide further visual feedback.

4 PILOT USER CONTROL SYSTEM VALIDATION STUDY

The goal of this validation study was to assess the usability of the control system for conducting common gestures and interactions, with a focus on the pilot user. Participants wore a Manus VR glove, HTC Vive controller, and HTC Vive tracker to control the manipulator throughout this study.

4.1 Methods

Prior to each session, participants were given an approximate 5-minute training tutorial to become familiar with the control system, the user interface (see Figure 4), and the procedures of the experiment. Participants were then asked to perform 14 specified gestures in a natural manner (see Figure 5) and provide verbal feedback on each. Two of the 14 gestures ("Fist Bump" and "High Five") were physically interactive gestures, during which the participants controlled the robot to interact with an experimenter acting as a local user. The other 12 gestures were individual gestures performed without physical interaction with a local user. After each gesture, participants were asked whether the system passed or failed at replicating the gesture. They were then asked for a numerical rating between 1 and 10, with 1 being "the system was not at all useful for replicating my gesture" and 10 being "the system was very useful for replicating my gesture." Additionally, participant comments about the system's performance during or after the gesture were recorded. At the end of the session, participants were asked to rate the ease of use of the control system as a whole on a scale of 1 to 10, with 1 being "very difficult to use" and 10 being "very easy to use." Participants were also asked open-ended questions, including "How easy or difficult was learning and using the remote control system?" and "Do you have any suggestions for the improvement of the control system or the robot response overall?" Eight volunteers participated in this study

Fig. 5. Gestures performed by users during testing.

for a total of 112 gestures. The eight participants were engineering graduate students who had not previously teleoperated the robot. The study took place in a small lab space outfitted with the pilot user hardware, with the telerobot located in a separate larger lab space. Each session took approximately 20 minutes to complete. The study was approved by the university's Institutional Review Board.

4.2 Results and Discussion

The results are shown in Table 2. Nine out of the 14 gestures had a 100% pass rate. These passing gestures include Fist Bump, Wave, Thumbs Up, Thumbs Down, Come Here, Point to Table, Point to Person, Point to Chair, and Point to Door. Of the remaining 5 gestures, "High Five" had a 75% pass rate, "Peace Sign" had a 62.5% pass rate, and "A Tiny Bit," "Stop," and "Point to Self" had a 50% pass rate. This averages to 84.82 ± 21.22% of gestures effectively replicated according to pilot users.

The gestures with 100% pass rate all had similar comments from participants—that the gestures "worked well," "felt natural," or were "nice." "Point to Table" was found to have the highest rating with a mean of 8.5 ± 1.00, with "Thumbs Down" being a close second with a rating of 8.38 ± 0.86. Concerning the gestures, "Stop," "Peace Sign," and "A Tiny Bit," participants said the fingers felt "unresponsive." Although the Brunel Hand 2.0 includes hardware limits on finger abduction and adduction, we suspect the unresponsive feeling of the finger tracking is due to the Manus VR Prime I glove, which has imperfect finger flexion tracking. Making the fingers more responsive may be achieved by adding a multiplier to the signal generated by the Manus VR Prime I glove to exaggerate finger flexion.

Some of the comments stated that adding a motor to facilitate extension and flexion of the wrist would allow movements such as the "High Five," "Stop," and "Point to Self" gesture to be performed more realistically and naturally. "Come Here," although it had an 100% pass-fail rating, scored only 6.75 ± 1.71 out of 10, and it also had comments about the lack of wrist extension and flexion on the robotic manipulator. We observed that some participants could compensate for the missing DOF

Table 2. Pilot User Control System Usability Results (n = 8)

Gesture	% Passed	Mean Rating (1–10)
Fist Bump	100	8.25 ± 0.97
High Five	75	5.88 ± 1.90
Wave	100	8.06 ± 1.18
Thumbs Up	100	7.94 ± 1.84
Thumbs Down	100	8.38 ± 0.86
"A Tiny Bit"	50	5.38 ± 2.29
"Come Here"	100	6.75 ± 1.71
"Stop"	50	5.38 ± 2.29
Peace Sign	62.5	5.88 ± 2.37
Point to Table	100	8.50 ± 1.00
Point to Person	100	8.13 ± 0.93
Point to Chair	100	7.88 ± 2.09
Point to Door	100	7.88 ± 1.96
Point to Self	50	4.88 ± 2.66
Mean User Rating	**84.82 ± 21.22**	**7.08 ± 1.32**

User ratings for each gesture were provided as pass-fail and on a scale of 1 to 10, with 1 being "not at all useful" and 10 being "very useful." Mean control system ease of use (not shown in this table) as reported by participants was 7.13 ± 0.93.

in the wrist by bringing their hand closer to their body and bending their elbow. This correction was done without participants commenting on it, which indicates that the control system helped the participants learn to compensate for the missing DOF subconsciously.

An additional improvement that can be easily implemented is correcting the inability of cross-body movement. In its current state, the manipulator is not able to cross the plane directly in front of the shoulder parallel to the sagittal plane of the body due to hardware limitations. This issue was especially noticeable during the "Point to Self" and the "Point at Chair" gestures depending on how they were executed by the user. "Point to Self" was given the lowest rating, with the average being 4.88 ± 2.66, and it had comments about the gesture being "impossible to perform" or that it would not be easily seen as a self-reference because of the cross-body limitation. Addressing this issue, the hardware on the shoulder joint can be slightly modified to permit another 10 to 20 degrees of movement across the body, allowing for a larger range of motion.

Another concern voiced was visibility. Although four of the "pointing" gestures passed 100% of the time, users commented that it was sometimes hard to visualize if the manipulator was pointing in the right direction. With regard to proxemics, pointing is a demonstrably challenging gesture to perform, as is noted in the work of Mead et al. [26]. "High Five" had concerns about the visibility of the hand when trying to target another person's hand. As the system is currently set up, there is a fisheye camera above the arm to allow visibility of arm motion. Some users noted that the distortion in the fisheye lens made it difficult to judge the arm position with respect to the user position. This situation can be improved by using a different camera and/or placement. Additionally, the camera on top of the monitor points at the face of local users. This camera was not implemented at the time of the experiment because facial expressions from the local user were not necessary in this study, but it may help visualize the manipulator during higher gestures such as "High Five."

The participants rated the overall remote system usability as 7.13 ± 0.93 on the 1 to 10 scale. Some of the positive comments that were frequently stated involved the system being "easy to use"

Table 3. Demographics for Participants (n = 111, 31 Male, 80 Female) and Confederates (n = 19, 4 Male, 15 Female)

Ethnicity	Participants	Confederates
Caucasian	55.0%	84.2%
African American	27.0%	10.5%
Hispanic/Latin American	7.2%	–
Asian/Asian American	7.2%	5.3%
Bi-cultural/Mixed/Other	3.6%	–
Mean Age	**19.83 ± 2.23**	**–**

and "cool," and that most of the gestures worked well and felt "natural." Some negative comments suggestive of possible improvements to the system include the responsiveness of the arm being "slow" or "laggy" in some instances. Addressing response time will require enhancements to the PID control tuning and reducing processing complexity and data transfer volume.

In closing, with a participant-reported overall gesture replication success rate of 84.82 ± 21.22% and an average overall ease of use rating of 7.13 ± 0.93 out of 10, the results demonstrate promise in the usability of replicating interactions and gestures within the current system. Further, many participant-reported areas for improvement such as better finger motion mapping, wrist flexion/extension compensation, and cross-body range of motion involved the local manipulator rather than the pilot user system. Limitations of the study include the small sample size and limited training and exposure of the system for pilot users. These limitations should be considered in interpreting the results. It should be noted, however, that because this was the first exposure and use of the system for participants, these findings are particularly positive considering the complexity of the system, and performance improvements would be expected with additional training and experience.

5 EXPERIMENTAL STUDIES

The final experimental studies were designed to determine if the addition of expressive gesturing and tangible interactions impacted the social connection between the pilot user and the local user. The study also investigated whether the addition of the manipulator impacted each user's perception of the robot and anxiety of interacting with the robot. We conducted a series of four experiments: (1) a participant, as a local user, interacts with a confederate pilot user via the telerobot without the manipulator attached; (2) a participant, as a local user, interacts with a confederate pilot user via the telerobot with the manipulator attached and operated by the confederate; (3) a participant, as a pilot user, interacts with a confederate local user via the telerobot without the manipulator attached; and (4) a participant, as a pilot user, interacts with a confederate local user via the telerobot with the manipulator attached and operated by the participant. In both the pilot and local user conditions, we hypothesized that participants in the condition of using the robot with the arm would have a more positive experience than those in the robot without the arm condition. Specifically, we hypothesized that users in the interactions using the arm condition would (1) experience greater social connection toward one another, (2) experience lower immediate anxiety toward interacting with the robot, (3) have higher positive perceptions of the robot, and (4) have a more positive rating of their overall experience.

5.1 Methods

5.1.1 Procedure. Participants were 111 undergraduate (31 male and 80 female) students enrolled in an introductory psychology course (Table 3). All subjects were recruited through the

Fig. 6. The experimental setup of the local user experiments illustrating a subject interacting with the telerobot with the arm attached. The same set-up was used for the no-arm condition with the same robot, but the arm was removed.

Research Participant Pool run by the SIUE Department of Psychology. The study had Institutional Review Board approval.

Participants in the local user conditions interacted with other participants (trained confederates) via the robot with the arm (n = 33) or without the arm (n = 23), as shown in Figure 6. Participants in the pilot user conditions interacted with other participants (trained confederates) via the robot with the arm (n = 19) or without the arm (n = 36) by controlling the robot. Each participant experienced only one of the four conditions. Confederates were exclusively researchers but were introduced as fellow participants. The confederates consisted of 19 undergraduate (15 female and 4 male) psychology research assistants (see Table 3). All confederates were trained in up to three practice sessions and with protocols that were used to promote consistency in the study. The protocols included both scripted verbiage of what the confederate should say and when, along with which gestures should be used and when to support the interaction. For example, confederates were given scripts on how to initiate the conversation and the game of rock-paper-scissors along with guidance on which gestures to use at specific points. Four versions of the confederate protocol (two for pilot users and two for local users) were developed, varying only by the order and timing of specific elements that were inherently different across conditions. The same five gestures and scripted verbiage were used regardless of the study condition. The gestures included lifting the arm to say "I don't know," thumbs-up, raising the arm into the air to celebrate if the confederate won the game of rock-paper-scissors, fist bump, and waving "hello" and "goodbye." Each of these gestures was paired at timing that was appropriate within the script of the conversation. The local user condition took place in a large lab space where the robot with or without the arm was placed. The pilot user condition took place in a separate small lab space outfitted with the necessary pilot user hardware. In all conditions, participants were monitored by one experimenter and received no assistance outside of the training.

In all conditions, participants first completed online questionnaires assessing their anxiety toward the robot during interactions (**Robot Anxiety Scale (RAS)**) in addition to demographic questions. Participants were then asked to interact with other participants via the robot with or without the arm. Pilot users in the conditions without the arm performed gestures such that they were visible on the robot's video screen.

The researcher first asked the confederate to start by introducing him/herself. He or she then asked the participant about their major, where they are from, and where they live. If the participant asked any questions, the confederate answered. Participant pilot users in the arm condition were instructed to move naturally while operating the arm, whereas those in the no-arm condition received no additional instructions. The researcher then asked the participant and the confederate to engage in a game of rock-paper-scissors and told them that the winner would receive a prize for participating. This was done to increase participant engagement in the interaction while also increasing expressive gestures. After this, the experimenter asked the participant and the confederate to continue the interaction for about 1 more minute. Each interaction lasted about 10 to 15 minutes, and both the participant and the confederate were given a university pencil for participation upon completion.

After the interaction, participants were asked to complete additional questionnaires assessing various psychological constructs including post-task affect, anxiety toward the robot (RAS), and perceptions of the robot (Godspeed). In addition, participants' behavior and facial expressions during the interaction were assessed.

We first ran the experimental sessions for the local user and pilot user conditions without the arm in Spring 2019, and participants were randomly assigned into one of those two conditions. Then, after Fall 2019, we ran the sessions for the local user and pilot user conditions with the arm. Although we planned to run even numbers across groups, disruptions from the pandemic resulted in differences across them. This is a limitation of the current study that should be noted in the interpretation of the results.

5.1.2 Measures.

Anxiety Toward the Robot. We measured anxiety toward the robot by using the RAS [32]. Although this scale is intended to measure anxiety in human-robot interactions, we wanted to examine if participants differed in their general anxiety toward the telerobot with and without the arm, as the physical presence of the telerobot itself impacts the local user's perception of the pilot user's social presence [10]. The scale consists of 11 items classified into three sub-scales: (1) anxiety toward communication capacity of robots (e.g., "Will the robot understand difficult conversation topics?"), (2) anxiety toward behavioral characteristics of robots (e.g., "How fast will the robot move?"), and (3) anxiety toward discourse with robots (e.g., "How should I talk to the robot?"). Participants were asked to respond to these questions using a 6-point scale ranging from 1 ("I do not feel anxiety at all") to 6 ("I feel very anxious"). We averaged scores such that higher scores indicate that they experienced more anxiety toward the robot. Cronbach's alpha for this scale before the interaction was .95 and after the interaction was .97.

Post-Task Self-Report Measures. Participants were asked to rate the extent to which they felt anxious, content, enthusiastic, confident, sad, nervous, and uneasy after the interaction on a 5-point scale adopted from a previous study [40] ranging from 1 (strongly disagree) to 7 (strongly agree). After reverse-coding four negatively valenced items, we averaged scores such that higher scores indicate more positive affect to create a single affect scale. Cronbach's alpha for this scale was .86. In addition, participants rated the extent to which they were concerned about what their interaction partner (the confederate) thought of them, how much they liked the partner, how much they enjoyed the interaction, and how much they thought the partner enjoyed the interaction on the same 5-point scale.

Perceptions Toward the Robot. We measured perceptions toward the robot by using the Godspeed questionnaire [7]. As with the use of the RAS, we wanted to determine if the addition of the manipulator altered user perception of the telerobot, as this demonstrably affects the social presence of the pilot user [10]. The scale is intended to measure five key concepts in human-robot interaction: (1) anthropomorphism, (2) animacy, (3) likeability, (4) perceived intelligence, and (5) perceived safety. This measurement employs semantic differential scales. For instance, participants rated their impression of the robot from 1 (fake) to 5 (natural) for anthropomorphism, from 1 (dead) to 5 (alive) for animacy, from 1 (dislike) to 5 (like) for likability, from 1 (incompetent) to 5 (competent) for perceived intelligence, and from 1 (anxious) to 5 (relaxed) for perceived safety. Cronbach's alpha for the 5-item anthropomorphism was .94, six-item animacy was .95, five-item likability was .96, five-item perceived intelligence was .96., and three-item perceived safety was .80.

Interaction Behaviors and Facial Expressions. We also video-recorded the interaction between the participant and the confederate. Three coders independently recorded how long (in seconds) they engaged in the interaction, how many questions participants answered to the confederate's questions, and how many questions participants asked to the confederate. Cronbach's alpha for interaction duration was .99, the number of questions answered was .90, and the number of questions asked was .98. In addition, two coders independently recorded how many times participants smiled and frowned during the interaction. Cronbach's alpha for smiling was .93. We did not analyze the frowning data due to its low reliability (.26).

5.2 Results

A series of t-tests were separately performed for the local user conditions and the pilot user conditions to examine the effects of interacting via the robot with the arm versus the robot without the arm on psychological constructs measured in this study.

Local User. For the local user conditions, the analysis of the post-task self-report measures indicated that participants in the robot with the arm condition reported more positive affect ($M = 5.44$, $SD = 1.14$) than those in the robot without the arm condition ($M = 4.67$, $SD = 1.02$), $t = -2.59$, $p = .01$, $d = .71$. In addition, participants reported that they enjoyed the interaction with the other person more ($M = 6.36$, $SD = .78$) than those in the robot without the arm condition ($M = 5.87$, $SD = .87$), $t = -2.22$, $p = .03$, $d = .59$. These results suggested that participants in the robot with the arm condition were more comfortable interacting with other participants than those in the robot without the arm condition. However, the analysis of the RAS indicated that although participants in the robot with the arm condition reported less anxiety toward the robot ($M = 2.52$, $SD = 1.03$) than those in the robot without the arm condition ($M = 2.95$, $SD = 1.09$), the effect did not reach the conventional levels of significance, $p = .14$.

Interestingly, the analysis of Godspeed questionnaires indicated that participants who interacted with the robot perceived the robot with the arm lower in anthropomorphism ($M = 5.90$, $SD = 2.46$) than the robot without the arm ($M = 7.59$, $SD = 3.24$), $t = 2.19$, $p = .03$, $d = .59$. Additionally, participants perceived the robot with the arm condition lower in animacy ($M = 4.96$, $SD = 1.68$) than the robot without the arm ($M = 6.14$, $SD = 2.16$), $t = 2.30$, $p = .03$, $d = .61$. These results suggest that participants actually perceived the robot with the arm less human-like than the robot without the arm. This presents an interesting tension. The lower animacy ratings could be the result of participants perceiving the arm as an extension of their interaction partner rather than of the robot. However, the lower anthropomorphism ratings may be reactions to the mechanical complexity that the arm adds to the system. The behavioral coding data indicated that participants in the robot with the arm condition talked longer ($M = 359.29$, $SD = 99.31$) than those in the robot without the arm condition ($M = 295.00$, $SD = 132.38$), $t = -2.07$, $p = .04$, $d = .57$. Furthermore, they smiled more (M = 15.61, SD = 7.03) than those in the robot without the arm condition (M = 10.82, SD = 4.71), $t = -2.79$, $p = .007$, $d = .77$.

The results overall suggested that local user participants were satisfied with and engaged in the interaction via the robot with the arm more than the robot without the arm. However, they perceived the robot as less human-like when they interacted with the robot with the arm compared to when they interacted with the robot without the arm. The differences in this engagement potentially arose from the novelty of the arm. Participants' perceptions of interactions may have been influenced by excitement and interest over its presence.

Pilot User. For the pilot user conditions, however, there were no significant differences in participant perception of the interaction between the arm conditions. The analysis of the post-task self-report measures indicated that although participants in the robot with the arm condition reported more positive affect (M = 5.16, SD = 1.06) than those in the robot without the arm condition (M = 4.88, SD = 1.11), the effect did not reach conventional levels of significance, $p = .38$. All other post-task self-report measures did not show significant results, $p_s > .23$. The analysis of the RAS also indicated no significant difference regarding anxiety toward the robot depending on the condition, $p = .89$. However, the analysis of Godspeed questionnaires revealed fairly consistent results across five variables. Participants who controlled the robot perceived the robot with the arm lower in anthropomorphism (M = 4.88, SD = 2.75) than the robot without the arm (M = 9.06, SD = 2.91), $t = 5.13$, $p < .001$, $d = 1.48$. Participants perceived the robot with the arm condition lower in animacy (M = 4.62, SD = 1.78) than the robot without the arm (M = 7.06, SD = 2.07), $t = 4.30$, $p < .001$, $d = 1.26$. Participants perceived the robot with the arm condition lower in likability (M = 6.47, SD = 1.45) than the robot without the arm (M = 7.90, SD = 1.29), $t = 3.70$, $p = .001$, $d = 1.04$. Participants perceived the robot with the arm condition lower in intelligence (M = 5.98, SD = 1.46) than the robot without the arm (M = 7.83, SD = 1.21), $t = 4.99$, $p < .001$, $d = 1.38$. Finally, there were marginally significant results that participants perceived the robot with the arm condition lower in safety (M = 6.60, SD = 1.47) than the robot without the arm (M = 7.36, SD = 1.43), $t = 1.86$, $p = .07$, $d = .52$. The behavioral coding data also indicated that participants interacting with the robot with the arm asked fewer questions (M = 4.48, SD = 3.24) than those interacting with the robot without the arm (M = 7.21, SD = 4.85), $t = 2.05$, $p = .045$, $d = .62$, suggesting that they were less engaged in the interaction. Thus, these results suggest that participants actually perceived the robot with the arm less human-like than the robot without the arm.

5.3 Discussion

Local User. The results of the local user conditions overall suggested that the robot with the arm elicited a more positive experience than the robot without the arm. Participants reported more favorable impressions toward the interaction partner and the interaction itself when they interacted via the robot with the arm compared to when they interacted via the robot without the arm. Additionally, video coding data demonstrates that local user participants engaged in longer conversations and shared more favorable facial expressions (smiles) in the robot with the arm condition than the robot without the arm condition. Although these results suggest promise in increasing social connection, more rigorous measures are necessary to support this case. Overall, these results appear to support our hypothesis that the addition of the tangible interactions and expressive gesturing increased the positive rating of the overall experience. However, some impact may be due to confounding effects of the arm's novelty and capabilities. Interestingly, participants in the local user conditions perceived the robot less human-like when they interacted via the robot with the arm. The arm's mechanical appearance potentially contributed to the perception that participants were interacting with the robot itself rather than the interaction partner. This could also possibly be explained by the participant identifying the arm movement with the interaction partner. The Godspeed sub-scales of anthropomorphism and animacy are measurements of robot autonomy; therefore, by attributing the tangible interactions and expressive gesturing of the telerobot to the interaction partner, it would be expected that the participant would score these characteristics lower. If so, these results would also add credence to our hypothesis of (1) increasing the social connection to the pilot user. This would also explain why the results did not uphold the hypothesis of (2) a higher positive perception of the robot. Finally, although the results tended to uphold our hypothesis of (3) lower anxiety, they did not reach a level of significance.

Pilot User. Although the results tended to uphold our hypothesis of (1) increasing social connectedness, they did not reach a level of significance. The results also did not support our hypothesis of (4) a higher positive rating of the overall experience. We conjecture that this result is due to a high cognitive load and anxiety of using a novel controller. Although we allowed for a short training time, this may not have been sufficient for the subjects to attain a comfort level with the system. More specifically, participants may have had to focus too much on the process of creating the gestures, pulling their attention away from the social interaction. As mentioned earlier, the Godspeed sub-scales of anthropomorphism, animacy, and intelligence are measures of perceived autonomy; therefore, with the participant in direct control of the robot platform, it is not surprising that the post-task results showed a significantly lower rating, and thus not supporting our hypothesis of (2) higher positive perception of the robot. Finally, the results also did not support our hypothesis of (3) lower anxiety toward the robot overall. This, again, may be attributed to the novelty of operating the system, which may subside with more experience.

6 CONCLUSION AND FUTURE WORK

In this work, we presented a modified telerobotic platform augmented with a lightweight, anthropomorphic manipulator to enable expressive gestures and tangible interactions. We also presented and validated a pilot user interface system for controlling the manipulator, demonstrating that the telerobot system can replicate intended pilot user gestures and interactions with a greater than 80% pass rating by the pilot users themselves. Through experimental studies comparing the social connection of local users and pilots users, we determined that local users significantly benefit from an enhanced connection experience when interacting with a telerobot with a manipulator, but pilot users do not. Future work will focus on improving the pilot user experience, specifically with a focus on lowering the cognitive workload and complexity of operating the manipulator and by investigating shared control schemes that can support pilot users in executing complex social interactions (e.g., handshakes, high fives). Additionally, although the current manipulator was designed for QB, a universal manipulator design that is compatible with multiple telerobotic platforms is currently in progress. Finally, the local user intrinsically received "haptic" feedback in the interactions, whereas the pilot user did not. We hypothesize that this lack of haptic feedback is particularly critical for pilot users in executing and engaging in social contact interactions. Future work will focus on providing haptic feedback in a meaningful, intuitive way for the pilot user. In closing, this work sets the stage for future rich investigations in mediated social touch interaction on telerobotic platforms, whereby new haptic experiences for both local and pilot users can be imagined and created.

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