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Robot Telekinesis: Application of a Unimanual and Bimanual Object Manipulation Technique to Robot Control

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Abstract—**Unlike large and dangerous industrial robots at production lines in factories that are strictly fenced off, collaborative robots are smaller and safer and can be installed adjacent to human workers and collaborate with them. However, controlling and teaching new moves to collaborative robots can be difficult and time-consuming when using existing methods, such as pressing buttons on a teaching pendant and physically grabbing and moving the robot via direct teaching. We present Robot Telekinesis, a novel robot interaction technique that lets the user remotely control the movement of the end effector of a robot arm with unimanual and bimanual hand gestures that closely resemble handling a physical object. Through formal evaluation, we show that using a teaching pendant is slow and confusing and that direct teaching is fast and intuitive but physically demanding. Robot Telekinesis is as fast and intuitive as direct teaching without the need for physical contact or physical effort.**

Fig. 1. Robot Telekinesis lets the user remotely control the movement of the end effector of a robot arm with hand gestures that closely resemble handling a physical object.

I. Introduction

A new breed of small and safe robot arms called collaborative robots are entering the workplace. Unlike large and dangerous industrial manipulators in factories that must be strictly separated from human workers, collaborative robots can be installed in close proximity of human workers and collaborate with them side by side. These robots can assist in repetitive tasks with high speed, precision, and endurance so that human workers can focus on creativity and critical decision-making [1] for increased overall productivity [2].

Collaborative robots are expected to reach new, complex, and ever-changing workplaces where the application of robots was previously unviable, such as a cramped workshop or a busy kitchen. Unlike production lines in factories, the configuration and tasks in these workplaces may frequently change, so a way to quickly program new moves for new tasks in new configurations is needed. However, controlling and teaching moves can be difficult and time-consuming using existing methods, especially for nonexperts.

In this paper, we propose Robot Telekinesis, a novel interaction technique that lets the user move the end effector of a robot arm with hand gestures that closely resemble handling a physical object (Fig. 1). Using our technique, the user can quickly and easily control the robot from a distance, as if physically grabbing and moving the robot, without actually making the physical contact or the physical effort. Moreover, the user can utilize fluid clutching with one, two, and between hands to make larger movements or to make movements with more comfortable gestures.

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II. Related Work

Envisioning humans and robots working together, Colgate et al. first coined the term collaborative robot, or cobot [3], for a class of mechatronic assistive devices [4]. The motivation behind cobot was the recognition that some tasks cannot be fully automated [4] and that human sensing and decision-making are required for complex and variable tasks [5]. Such a collaboration necessitates an effective method of controlling and teaching the robot.

However, controlling the movements of a complex robot with many degrees of freedom (DOF) in real time is an inherently difficult task. Within the robotics community, a common approach has been capturing real-time movements of a human user (master) and mapping them to those of a robot (slave). Researchers have used various kinematic rigs [6] or optical sensors [7, 8] to capture movements of the user's body and generated robot movements from them.

With adequate visual and haptic displays, the master–slave technique can elicit an experience of stepping inside the robot's body [9]. Perceiving and controlling the robot as a part of one's own body can improve performances of mission-critical tasks in extraordinary circumstances, such as space exploration [10], nuclear reactor maintenance [9], explosive ordnance disposal [11], and medical surgery [12, 13].

However, there are scenarios in which controlling the robot from the first-person viewpoint is undesirable. For instance, due to blind spots, occlusion, and disorientation, the best viewpoint for controlling the robot may be from the outside [14, 15] and may even frequently change [16, 17].

Moreover, in the case of collaborative robots, the user may be instructing the robot to interact with him or her directly, e.g. to bring a component or take it away from his or her hand. Such scenarios require the user to step outside the robot's body and treat the robot as a foreign, remote object.

On the other hand, within the human–computer interaction (HCI) community, interaction techniques that closely resemble handling a physical object have enabled intuitive and effective real-time manipulation of remote virtual objects, such as 3D CAD models, in virtual scenes.

Ware and Jessome suggested a technique where an object is simultaneously translated and rotated with one hand gestures that resemble holding and moving a physical object with one hand [18]. Mapes and Moshell suggested a technique where an object is simultaneously translated, rotated, and scaled with two hand gestures that resemble holding, moving, and stretching a physical object with two hands [19]. Hinckley et al. stressed the importance of using relative as opposed to absolute motion and an easy clutching mechanism for the cognitive and ergonomic ease of spatial manipulation [20]. Feng et al. presented a detailed survey of existing unimanual and bimanual techniques for virtual object manipulation [21].

While the design decisions of some novel methods seem to partially reflect similar considerations [22, 23], ours is the first to apply a unimanual and bimanual interaction technique extensively studied by the HCI community in the context of remote virtual object manipulation to the movement control of a physical robot, to the best of our knowledge.

Finally, CoBlox [24] is a block-based coding interface that makes robot programming, such as event handling and control flow, easier for novices. While it uses an on-screen widget-based interface for the movement control, we believe that more intuitive techniques like ours can complement it.

III. Robot Telekinesis

Robot Telekinesis is an interaction technique for controlling the real-time position and orientation of the end effector of a robot from a distance, using one and two hand gestures that resemble holding and moving a free-floating plane in space. Our technique allows fluid clutching with one, two, and between hands for high dexterity and comfort.

Initially, the user holds two low-cost, lightweight 6-DOF motion-tracked controllers. By activating the controllers, the user can create and hold a virtual plane (Fig. 2) with one hand (e.g. as if holding a small plate in Fig. 2c, f) or two hands (e.g. as if holding a large tray in Fig. 2i). At the same time, another virtual plane with the same orientation is created at the position of the end effector of the robot (Fig. 3).

When the handheld plane is translated and rotated, the motion deltas are transmitted to the plane at the end effector in real time (Fig. 4). As a result, the end effector follows hand motions as if the user is holding and moving a plane that is physically attached to the end effector.

When the controllers are deactivated, the virtual planes are destroyed and the motion deltas are no longer transmitted, so the user can freely walk to a better standpoint or take a more comfortable posture without affecting the robot during transit. The user can activate and deactivate controllers at any time, in any order.

With clutching, e.g. repeatedly activating and deactivating one or two controllers, or alternatingly activating and deactivating left and right controllers, the user can repeat the same hand motion multiple times to make larger movements without overstraining the arm or the wrist.

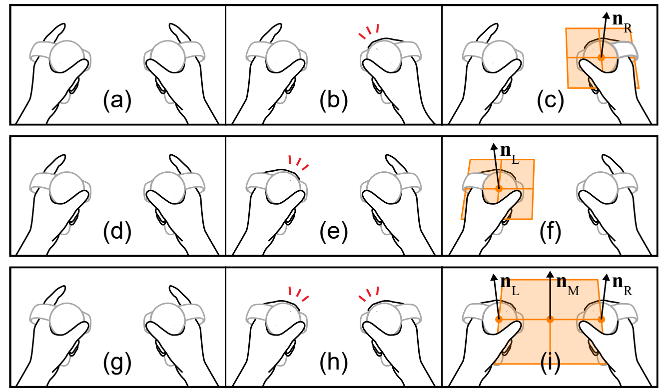

Fig. 2. (a, d, g) The user holds two 6-DOF controllers. When the user activates (b) the right or (e) left controller, a virtual plane with the normal (c) $\mathbf{n}_R$ or (f) $\mathbf{n}_L$ fixed to the controller is created. (h) When the user activates both controllers, (i) a virtual plane with the normal $\mathbf{n}_M$, the average of $\mathbf{n}_R$ and $\mathbf{n}_L$, is created at the midpoint between the two controllers.

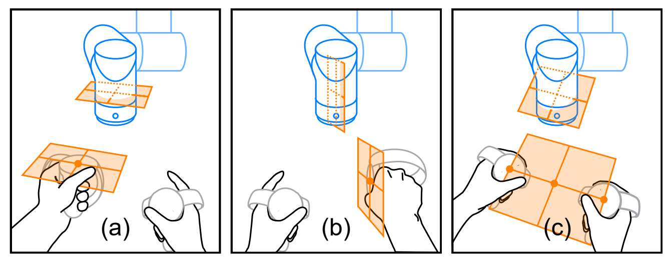

Fig. 3. When a virtual plane is created at (a) the left hand, (b) the right hand, or (c) the midpoint between the two hands, another virtual plane with the same orientation is created at the center of the end effector of the robot arm. The handheld plane acts as a motion proxy to the one at the end effector.

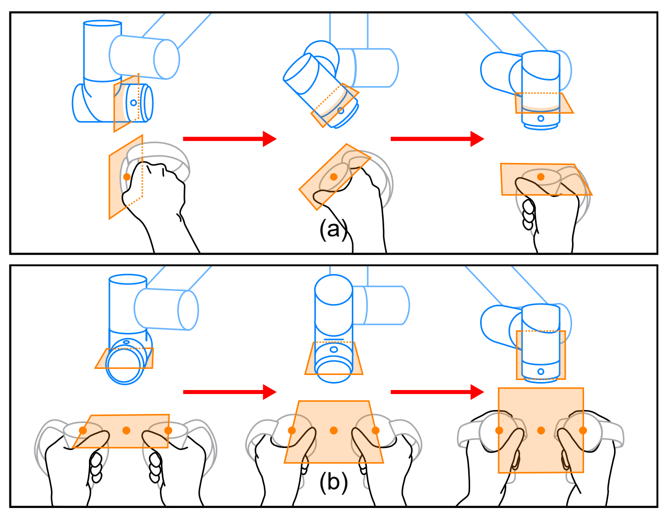

Fig. 4. When the handheld virtual plane is translated and rotated, the motion deltas of the handheld plane are transmitted to the end effector in real time. The user can thus control the end effector, as if physically holding and moving it by the planar handle, with (a) one or (b) two hands.

IV. Implementation

We implemented the Robot Telekinesis technique with the Universal Robots UR5 collaborative robot, a 6-axis robot arm with a working radius of 850 mm and a payload of 5 kg, and the Oculus Rift IR LED sensors and touch controllers that captured the 6-DOF motion of the two hands in real time. Note that the Oculus Rift VR headset was not used.

The Robot Telekinesis client was written in C# using Unity 3D engine and ran on an Alienware 15 gaming laptop, with a quad-core Intel Core i7 CPU clocked at 2.90 GHz, an NVIDIA GeForce GTX 1080 Max-Q GPU, and 16 GB of RAM. A relay server was written in JavaScript using Node.js runtime and ran on an Intel NUC mini PC, with a dual-core Intel Core i3 CPU clocked at 2.40 GHz and 4 GB of RAM.

Upon initialization, the client received the actual pose of the end effector of the UR5 robot from the relay server. Then, the client calculated the desired pose of the end effector based on the user's real-time hand motion acquired through the Oculus Rift sensors and sent the desired pose to the relay server. The relay server then issued discrete URScript move commands to the UR5 control unit at regular 10-ms intervals.

V. Evaluation

We evaluated Robot Telekinesis (RT) against two baseline techniques that are the only commonly available methods of controlling a collaborative robot: teaching pendant (TP) and direct teaching (DT), in a pick-up task that we designed to simulate a realistic workload in a moderately complex workspace that collaborative robots are meant for.

A. Participants & Procedure

12 volunteers (3 female, 9 male, age 20–32) participated. We recruited two groups of participants: 6 participants who had no previous experience of using a robot arm ("novices," P1–6), and 6 participants who had 3–10 years (6 years on average) of experience in the field of robotics ("experts," P7–12). All were right-handed except for one.

We used a mixed experiment design, where each participant tested all three techniques in a counterbalanced order. Since there were 3 techniques, there were 6 possible orders of presentation via permutation. The novice group and the expert group both tested all 6 orders of presentation.

For each technique, the participant was given a brief tutorial and could practice it for a few minutes until he or she expressed that he or she was ready. Each task was completed twice with each technique. After completing all tasks with all techniques, the participant was surveyed and interviewed.

B. Baseline Techniques

For TP (Fig. 5a), participants held the touchscreen-based UR5 teaching pendant with UR PolyScope GUI in one hand, and, with the other, pressed on-screen buttons mapped to the rate control of each joint's CW/CCW rotation or the end effector's translation and rotation in the global x, y, and z directions. For DT (Fig. 5b), the UR5's "Freedrive" mode was used, and participants physically grabbed and exerted force to move the robot arm using one or two hands. The UR5's maximum allowable speed was enabled for all techniques.

C. Task

Using each technique, participants picked up 10 equidistant (50 cm), numbered (#1–#10), square *Magformers* magnetic tiles (Fig. 6 red) placed at preconfigured positions and orientations across a tabletop workspace, in ascending order. A separate tile glued to the front-facing side of the end effector attracted target tiles when it was brought close and the orientations were aligned. The use of magnets eliminated the need for a gripper and the skill to operate it, so participants could focus solely on controlling the robot's movement.

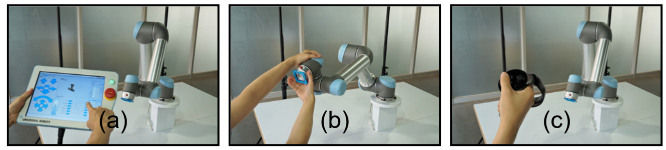

Fig. 5. Formal evaluation compared two baseline techniques: (a) teaching pendant (TP) and (b) direct teaching (DT), against (c) Robot Telekinesis (RT).

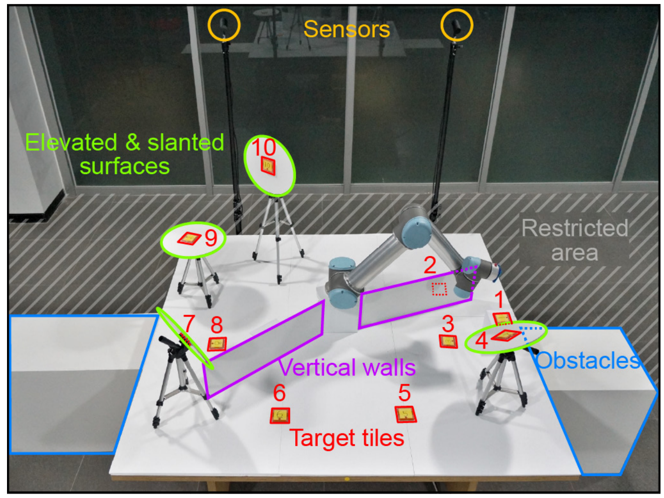

Fig. 6. Workspace setup. Using the above techniques, participants picked up 10 numbered magnetic tiles (red) in ascending order. Various fixtures (purple, green, blue) introduced additional elements of challenge.

We also introduced additional elements of challenge that the collaborative robot and its user would typically encounter in future workplaces, such as a cramped workshop or a busy kitchen, in the form of various fixtures that blocked the view, the robot path, and the walking path:

Going from tile #2 to #3 required the robot to take a detour path around an obstacle (Fig. 6 purple). Tiles #4 and #7 were laid on elevated and slanted surfaces (Fig. 6 green) requiring delicate control over the approach vector. Vertical walls occluded tiles #2 and #8 (Fig. 6 purple), and participants had to walk around the table to get a better viewpoint. Finally, the workspace was delimited by obstacles (Fig. 6 blue), so participants could not go too near tiles #2 and #10.

D. Measurement

The raw timestamped positions and orientations of the end effector were recorded for all techniques (Fig. 7). For RT, the activation status of the left and right controllers was recorded (Fig. 7c) for in-depth discussion of the usage pattern. For quantitative comparison, the task completion time was measured as the time it took the participant to move the robot from the initial position and pick up all 10 targets (Fig. 8). For qualitative comparison, 5-point Likert scale scores on questions based on NASA-TLX [25] were recorded (Fig. 9).

VI. Result

Overall, 235 minutes of robot movements were recorded. We used mixed ANOVA to test the significant main effects of the within-subjects (technique type) and between-subjects (expertise) factors on the dependent variable (task completion time). For post hoc analysis, pairwise comparisons were made with Bonferroni corrections. The results from the 2 trials that each participant performed with each technique type were averaged for the repeated measures analysis.

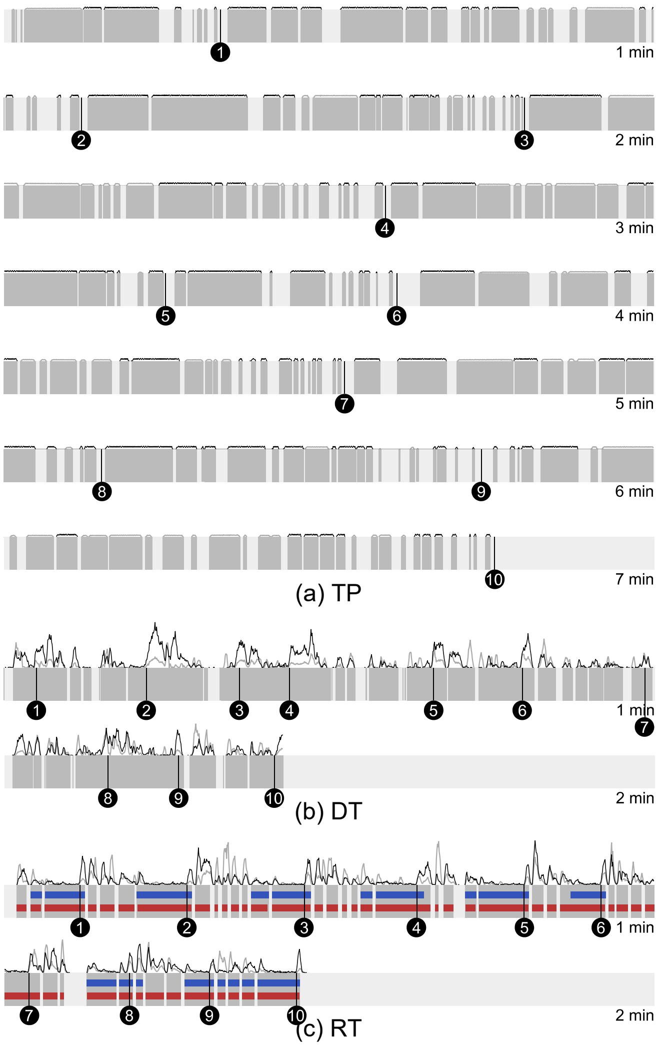

Fig. 7. Recorded performances of participants whose task completion time was the closest to the mean task completion time of each technique: (a) first TP trial of P11, (b) first DT trial of P8, and (c) second RT trial of P10. ■: robot is still, ■: robot is moving, ■: left hand is used, ■: right hand is used, ❶–❿: target is picked up, —: end effector translation speed, —: end effector rotation speed.

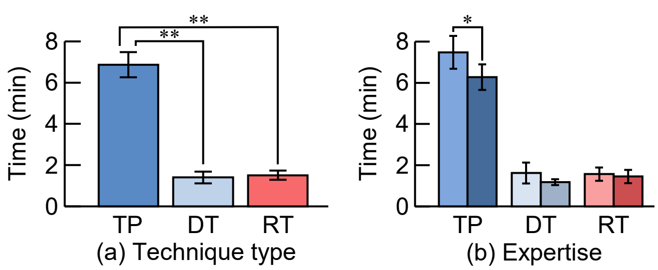

Fig. 8. Task completion time by (a) technique type, and (b) expertise. ■: TP, ■: DT, ■: RT, lighter shade: novices, darker shade: experts, error bars: ± 2 SE, *: $p < 0.05$, **: $p < 0.01$.

The technique type had a significant main effect on the task completion time (t) ($F_{2,20} = 403$, $p < 0.01$). There were significant differences between t_{TP} & t_{DT} ($p < 0.01$), and t_{TP} & t_{RT} ($p < 0.01$) but not between t_{DT} & t_{RT} (Figure 8a). The expertise also had a significant main effect on the task completion time ($F_{1,10} = 5.7$, $p < 0.05$). There was a significant difference between $t_{TP,\ novice}$ & $t_{TP,\ expert}$ ($p < 0.05$) but not between others (Figure 8b).

For the survey result, we used mixed ANOVA to test the significant main effects of the within-subjects (technique type) and between-subjects (expertise) factors on the dependent variable (5-point Likert scale score). For post hoc analysis, pairwise comparisons were made with Bonferroni corrections. The technique type had a significant main effect on the score (s) ($F_{2,20} = 43$, $p < 0.01$), but the expertise did not. The differences between all scores were significant ($p < 0.05$), except those between s_{DT} & s_{RT} on Q1, as well as s_{TP} & s_{DT} on Q2, Q4, and Q7 (Fig. 9).

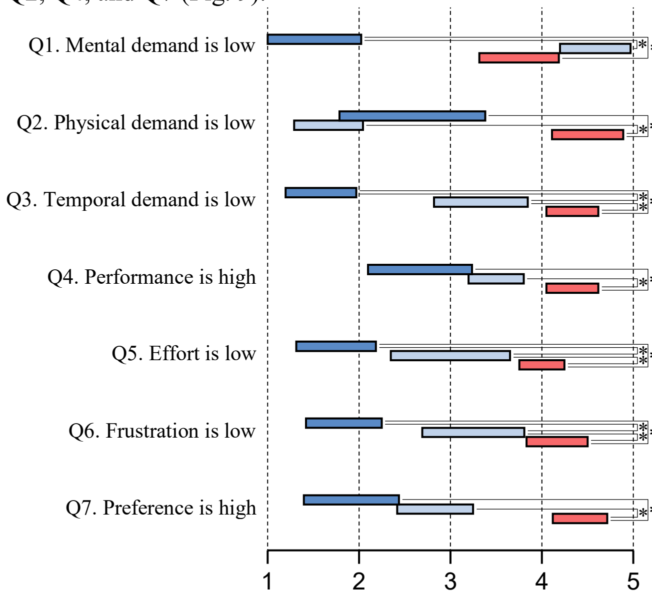

Fig. 9. Survey result on 5-point Likert scale. 1: strongly disagree, 2: disagree, 3: neutral, 4: agree, 5: strongly agree. ■: TP, ■: DT, ■: RT, horizontal bar: mean ± 2 SE, *: $p < 0.05$.

VII. Discussion

In this section, we discuss findings from the objective and subjective performance measures of the baseline techniques (TP and DT) and our proposed technique (RT). We also report an in-depth analysis of the usage pattern of RT.

A. *TP is Slow and Confusing*

Task completion with TP was more than 4 times slower (6' 52") compared to DT (1' 24") and RT (1' 31"). TP was found to be the most mentally (Q1) and temporally (Q3) demanding, requiring the most effort (Q5), and causing the most frustration (Q6) out of all the techniques. With TP, the novices took 19% more time compared to the experts (Fig. 8b).

Participants found the 24 buttons on TP (for translations along and rotations about the ± x, y, z axes, and CW and CCW rotations of each of the 6 joints) to be *"too many"* (P2, 3, 4), and it was *"difficult to memorize directions of buttons"* (P1, 2, 4, 6, 7, 10), especially when *"the viewing direction and button directions did not match"* (P5, 7, 8, 9) as the participants moved around the table. They were also distracted by having to *"frequently shift the attention between the robot and the hand-held controller"* (P4, 11).

Participants struggled to decompose desired movements into multiple discrete translations and rotations (P1, 2, 3, 7, 11) and resorted to *"frequent trial and error"* (P1, 2, 9, 10, 11). On average, each participant pressed buttons 23 times to go from one tile to the next, and 228 times overall.

B. DT is Fast and Intuitive but Physically Demanding

Task completion with DT was markedly faster than TP, and participants also found simply holding and applying force to move the robot with bare hands *"intuitive"* (all except P8). However, DT was found to be physically demanding (Q2).

Participants noted that the robot *"required too much force to move"* (all participants), and found it *"difficult to move delicately"* (P2, 5, 8). The end effector was especially difficult to rotate due to its smooth cylindrical shape and small diameter (P1, 7, 11, 12). While robots with more advanced torque compensation can be less affected by this issue, the UR5 used in our evaluation is very widely used in the industry and academia, and many users would be similarly affected.

Moreover, some tricky movements required participants to *"think about where the joints are"* (P1, 2, 4, 6, 11), figure out the inverse kinematics, and *"individually rotate them, step-by-step"* (P11) to obtain the desired end effector pose.

Participants also found it *"difficult to reach the target"* (P1, 4, 9, 10) when picking up targets #2 and #10 in the presence of obstacles. In these circumstances, the *"body posture was uncomfortable"* (P2, 4, 8, 12). In addition, the body posture could also be uncomfortable even when the target was clearly within reach. For instance, one participant found standing behind target #7 and pulling the end effector in toward her awkward and unwieldy (P2).

C. RT is as Fast as DT without the Physical Demand

With RT, participants performed tasks as quickly as physically holding and moving the robot (DT). In addition, RT received the most favorable mean scores (4.0–4.5) among all three techniques on all questions except for one on mental demand (Q1), where both RT and DT scored favorably.

Overall, participants found RT *"intuitive"* (P1, 2, 3, 5, 8, 9, 10, 11, 12), *"fast"* (P3, 4, 6, 9, 11), and *"lightweight"* (P2, 4, 9, 12). They appreciated that *"the robot follows the hand"* (P1, 2, 3, 5, 8, 9), as if *"pulling it by an invisible string"* (P4, 5). Some felt as if *"moving the robot like [one's] hand"* (P1) and even *"becoming one with the robot"* (P11), hinting at possible proprioceptive connections with the robot. One participant noted that, thanks to the low physical demand, *"fine control was easy,"* and that she could *"focus on the task"* (P4).

All participants could perform RT after practicing for less than 10 minutes, at a high level of subjective performance, as indicated by the favorable mean score of 4.3 on Q4. While some participants noted that it *"took some tries"* (P6, 8, 10), in general *"learning was quick"* (P1, 2, 10) and *"it clicked after trying a few times"* (P6).

D. One Hand for Large Strides, Both Hands for Fine Tuning

During the practice session, participants were explicitly instructed to use RT in whichever way they found convenient. They thus developed and exhibited distinct usage patterns.

First, participants primarily used the dominant hand (DH) rather than the non-dominant hand (NDH) (P1, 2, 3, 4, 7, 8, 9, 11), to make large strides of movements and quickly go from one target to the next (all except P6 and P12) (Fig. 10). One participant interestingly used her right hand for targets on her right-hand side (targets #1–#4) and her left hand for targets on her left-hand side (targets #7–#10) (P3) (Fig. 11).

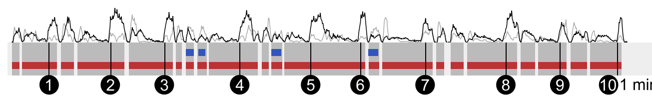

Fig. 10. Second RT trial of P7 in full. He primarily used the dominant hand, shown as many red bars and few blue bars. He made large strides with the dominant hand after picking up each target to quickly go to the next target, shown as highs in the black line graph over those red bars, to the right of numbered circles. ■: robot is still, ■: robot is moving, ■: left hand is used, ■: right hand is used, ❶–❿: target is picked up, —: end effector translation speed, —: end effector rotation speed.

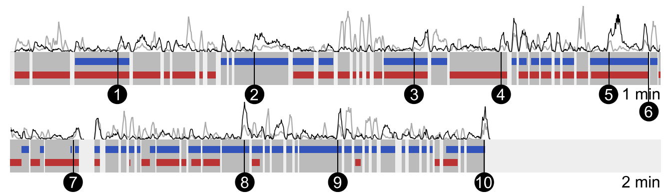

Fig. 11. First RT trial of P3 in full. She primarily used the right hand for targets on her right-hand side (#1–#4), shown as many red bars from the beginning to the 4th numbered circle, and the left hand for those on her left-hand side (#7–#10), shown as many blue bars from the 7th to 10th numbered circles. For the legend, see the caption of Fig. 10.

Second, many participants used both hands (BOTH) to make fine adjustments, particularly when carefully aligning the end effector to the target shortly before picking it up (P2, 3, 4, 5, 8, 9, 10, 11) (Fig. 12). Some participants used BOTH exclusively for the stability of control (P6, 12) (Fig. 13).

One participant separated the hands farther apart for even finer rotational adjustments (P3); just as with a steering wheel with a larger radius, the user can control the rotation more stably and delicately with a larger hand-to-hand distance.

Participants also used BOTH for decoupling translation and rotation of the end effector, e.g. translating without rotating (P1, 2, 3, 6, 9, 10) (e.g. concurrent blue and red bars, highs in the black line graph, and lows in the gray line graph in between the 5th and 6th numbered circles in Fig. 11), and rotating without translating (P1). Overall, participants found BOTH easier for rotating the end effector (P3, 4, 5, 6, 9, 11).

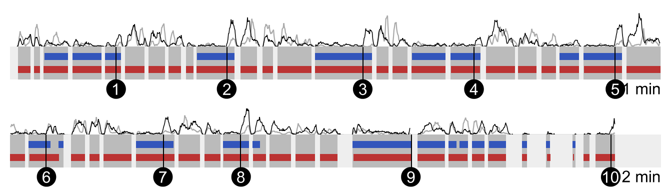

Fig. 12. Second RT trial of P9 in full. He used the dominant hand for large movements, shown as red bars and highs in the black and gray line graphs, and then both hands for fine adjustments shortly before picking up each target, shown as concurrent blue and red bars and lows in the black and gray line graphs to the left of the numbered circles. For the legend, see the caption of Fig. 10.

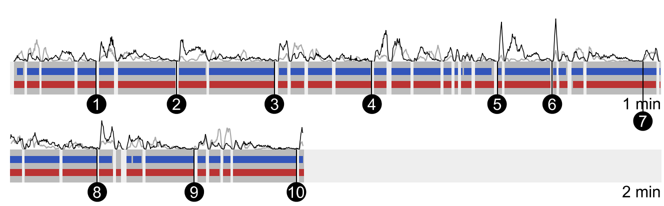

Fig. 13. Second RT trial of P6 in full. For the stability of control, he used both hands exclusively, shown as blue and red bars with identical lengths appearing together at all times. For the legend, see the caption of Fig. 10.

E. *Clutching for Comfortable Repetition*

Through clutching, all participants repeated hand motions to make larger movements within the comfortable ranges of motion of their hands, wrists and arms. They used clutching with DH for multiple large strides (e.g. many red bar segments with highs in the black line graph in Fig. 10), and BOTH for multiple fine adjustments (e.g. many concurrent blue and red bar segments with lows in the black and gray line graphs in Fig. 12). One participant alternatingly clutched between DH and NDH to make even larger movements more comfortably (P11) (Fig. 14).

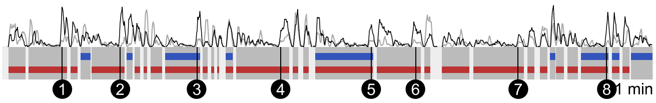

Fig. 14. First minute of the second RT trial of P11. He alternatingly clutched between hands in a hand-over manner to make even larger movements, shown as non-overlapping consecutive segments of red and blue bars and highs in the black and gray line graphs in between the 1st and 2nd, the 2nd and 3rd, and the 7th and 8th numbered circles. For the legend, see the caption of Fig. 10.

F. *RT is Suitable for Controlling and Teaching Ad Hoc Tasks in Complex and Dynamic Environments*

One participant (P11), who was the main operator of the humanoid robot that won the DARPA Robotics Challenge 2015 [26], noted that in complex environments, such as a disaster site, the ability to observe and operate the robot from the outside, as in RT, is critical for situational awareness and decision-making.

Another participant (P10), who was a member of the team that won the Surgical Robot Challenge 2018 [27], noted that while meticulous one-to-one master–slave correspondence is essential for the extremely high level of precision in surgery, RT could be useful in applications where the mobility and adaptability of the operator are prioritized.

Overall, expert participants agreed that RT is suitable for *"real-time remote operation"* (P7, 8, 10, 12), particularly in circumstances where the *"task is not predetermined"* (P12). By extension, RT would also be suitable in circumstances where moves are rapidly taught, performed a relatively small number of times, and then discarded when the task and the configuration change.

VIII. Conclusion & Future Work

While collaborative robots are rapidly making advances into new workplaces traditionally unoccupied by robots, the means of controlling and teaching them have not caught up.

In this study, we proposed Robot Telekinesis, a novel interaction technique that applies natural hand gestures extensively investigated in the human-computer interaction community, to performant manipulation of the position and orientation of the end effector of a robot arm, using only two lightweight and low-cost 6-DOF controllers.

In a formal evaluation that compared our technique against two most commonly used baseline techniques, a button-based teaching pendant and direct teaching, in a moderately challenging setting designed to simulate future workplaces, we found that our technique performs favorably in terms of objective and subjective measures.

We expect Robot Telekinesis to be used to quickly and easily control and teach new moves to a robot in complex and changing environments, where the time and effort required in doing so would be directly proportional to productivity.

Future work remains in providing visual and other sensory feedforward and feedback cues that could assist the user in avoiding and recovering from collisions, self-collisions, and singularities, as well as applying the technique to specific use cases in different physical scales, such as drone and motorized camera control.

Acknowledgment

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