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Assistive Telexistence System Using Motion Blending

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***Abstract*— Robotic avatar and telexistence systems have risen in prominence after the covid-19 pandemic, where current telecommunication methods are limited in terms of physical interaction abilities. Most existing systems focus on manual control of the remote robot, where the robot's arms and head movements follow the user's movements. Despite the effectiveness of such controls in conveying high levels of embodiment, such control methods jeopardize the efficiency of controls, especially for complex physical manipulation tasks, unclear environments, or unstable communication. Therefore, we propose an assistive-manipulation method to augment users' control of a telexistence robot during physical manipulation tasks. Machine Learning (ML) was used in the remote environment to localize target objects. This information is sent to the local environment where an inverse kinematic (IK) solution to hold the intended object is generated. The generated IK solution is fused with the one generated by the user's arm movements. The system enables generating various levels of IK fusion. However, an essential aspect of telexistence is to maintain high levels of embodiment and body ownership over the remote robot. Therefore, the evaluation in this paper focuses on investigating the effect of haptic feedback and the level of IK fusion on body ownership. The results indicate that haptic feedback induced a sense of assurance of task completion and enabling assistance from the system improved the user's sense of control over the robotic arm.**

***Keywords*—Motion Blending, Telexistence, Assistive Telexistence, Remote Manipulation, Virtual Reality, Haptic**

I. INTRODUCTION

Research on robotic Avatar and Telexistence systems has risen in prominence after the covid-19 pandemic systems [1]. Such systems offer a high level of embodiment, sense of immersion, and physical interaction capabilities beyond existing telecommunication mediums. Therefore, there are numerous projected benefits of these emerging systems in various domains, especially for medical and industrial tasks that require the physical presence of an expert to conduct physical interactions [2].

The majority of existing telexistence systems focus on manual control of the remote robot, where the robot's arms and head movements directly match the user's head and arm movements. Despite the effectiveness of such controls to convey high levels of embodiment [3], such control schemes jeopardize the efficiency of the robot's capabilities. Manual controls, that rely on the user to control all aspects of the system, are susceptible to various challenges, especially for complex physical manipulation tasks, unclear environments, or unstable communication to the remote environment [4]. These aspects present pressing challenges to manual controls. Similarly, relying on high levels of autonomy to ensure task efficiency can jeopardize the sense of agency and body ownership [5], thereby affecting the telexistence experience as a whole. Accordingly, providing a control method that provides adequate levels of autonomy while maintaining high agency is an essential research challenge for telexistence [6].

To address the mentioned challenge, we propose an assistive-manipulation method to augment users' control of a telexistence robot during physical manipulation tasks. To the best of our knowledge, this is the first work that attempts to introduce assistive manipulation capabilities with emphasis on telexistence. The proposed system comprises two main locations, a local site, where the control system is located, and a remote site, comprising the robot arm and head unit. Our control method of the robotic system at the remote site comprises three main steps: 1) the system recognizes and localizes potential objects the user wants to interact with within the remote environment and sends the information to the local site. 2) the system at the local site uses the sent information to generate an inverse kinematic (IK) solution based on the robot's structure to hold the intended object. 3) The generated IK solution is fused with the one generated by the user's arm movements at the local site. Accordingly, the generated movements fuse both the user's hand movements and the system-generated movements, and by controlling the level of fusion, we can determine the level of movement assistance during the task.

An essential aspect of telexistence systems is to maintain high levels of embodiment and body ownership over the remotely controlled system. In this work, we present a telexistence system that enables various levels of assistance for remote manipulation tasks. Moreover, we investigate the effect of haptic feedback and the presence of IK fusion on body ownership. The paper also discusses several insights for designing telexistence systems with assistive manipulation without jeopardizing body ownership.

II. RELATED WORKS

Several research papers had discussed the teleoperation and telexistence systems. The main difference between teleoperation and telexistence is the experience of the real-time sensation of existing in a remote location with emphasis on body ownership and embodiment [3] [4]. In this section, we discuss some papers about assistive manipulation methods and haptics within the scope of telemanipulation tasks.

Assisting the teleoperation to solve the problem of motion planning was introduced by Kamali et al. [7] by using dynamic

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goal deep reinforcement learning. The approach helps in performing intuitive mapping between the operator's hand motion to the robot arm while avoiding collisions. Zhang et al. [8] implemented a teleoperation system using VR and studied the efficacy of teaching the robot to do tasks using the imitation learning technique. However, these works support semi-autonomous teleoperation for high-level tasks and trajectory optimization and take away the control of the operator, therefore cannot be considered as assistance. The work presented in [9] and [10] implemented the concept of assistance without using Machine Learning (ML). Our work utilizes the ML to help in achieving assistance. In [11], the environment objects were detected but the detection was only used to raise the user's awareness of the remote environment. In paper [8], the environment is observed by using a depth camera, and the output is used later with the history of the robot's end effector's position to control the robot. On the other hand, the work presented in [12] suggested aiding the teleoperation by mapping the relative rotations. In [13] the assistance is given after predicting the user input to make sure that the level of assistance is suitable for the user and the situation, to make sure that the help is wanted by the user.

Haptics became an integral part of many telexistance systems. The work in [14], added sensors to detect the temperature, pressure, and vibration of the object, so the user can experience different sensations. Users can distinguish the surface texture of the object held by the robotic hand. a haptic telexistence system with a high DOF in the hand to give real hand movement for the robotic hand is also implemented in [15]. The finger-shaped haptic sensor was developed using GelForce technology which works on measuring the distribution of magnitude and direction of the force. In this project, a five-finger robotic hand and arm are implemented with haptic feedback to enable realistic interactions with the remote site. In addition to the remote head, the camera is controlled by the head movement with stereoscopic streaming to ensure a comprehensive vision of the remote site.

Telexistence has strict requirements in body ownership and embodiment, which must be satisfied to maintain high agency. To the best of our knowledge, this paper is the first to investigate telexistence with physical manipulation assistance, thereby attempting to introduce assistive manipulation while maintaining high levels of body ownership.

III. SYSTEM IMPLEMENTATION

The telexistence system comprises two sites. The local site is where the user controls the remote robot. The apparatus at the local site consists of a VR headset (HTC VIVE) [16], trackers to track the user's hand movement (HTC Vive), and a haptic glove as shown in Fig. 1. The remote site comprises the robot and head unit, which are both controlled by the user at the local site. The remote site consists of the head unit, robotic hand, and robotic arm as shown in Fig. 2. The implementation of each part of this system is discussed within each of the subsections.

Fig. 1. The system implementation on the local side

A. The Head Unit

The head unit, located at the remote site, is comprised of a camera mounted on three servomotors, which provide visual communication to the user at the local site. We used the ZED-M camera [17], to provide stereoscopic visual feedback to the local site. The stereoscopic video is streamed to the VIVE HTC VR head-mounted display (HMD) using GStreamer SDK [18]. GStreeamer was chosen as it can be configured to provide a high-quality video feed with minimal latency throughout the network.

To view the streamed video feed from the remote site, we created a Unity3D [19] scene which integrates and views the streamed GStreamer video. The stereoscopic video streamed from GStreamer is established using a custom pipeline to minimize latency and improve its quality as much as possible.

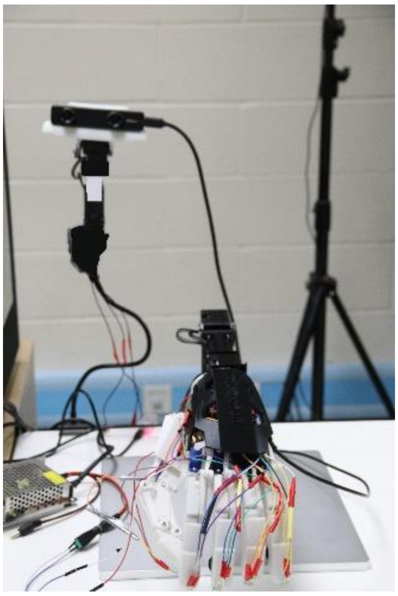

Fig. 2. The remote site of the system

Fig. 3. The Robotic Head Unit

The implementation of the head unit consists of a ZED-M camera which is placed on three DYNAMIXEL motors (Two DYNAMIXEL motors of type XL430-W250-T and one DYNAMIXEL motor of type XC430-W150-T). The three motors create a head unit that provides movement capabilities resembling human's natural head movements (as shown in Fig. 3), thereby allowing tilt, yaw, and roll rotations, as shown in Fig. 4.

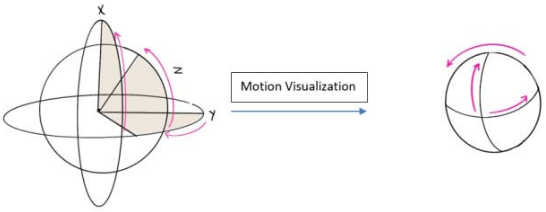

Fig. 4. The Head Motion Visualization on XYZ-axis.

The user at the local site uses the head-mounted display to control the head unit. We mapped the rotations around the three axes of the HMD directly to the head unit, so that the user's head movements are directly followed by the head unit in the remote environment. Similar to previous works [15][16] we used a client-server architecture to control the head unit servo motors through the network.

B. The Robotic Arm

Local site: We developed the control system of the robot using Unity3D. To control the robot arms, we used two VR trackers to control the robot, where one was used for localizing the robot in the real environment, and the other is mounted on the user's hand for controlling the robot arm's movements.

We developed an Inverse Kinematic (IK) robot model of the robot within Unity3D based on the work by Starke et al [20], as shown in Fig. 5. Using the IK model, we mapped the user's arm position to an IK objective for the robot to follow within Unity3D. Accordingly, the IK system generates a solution that follows the user's hand position as shown in Fig. 5. Each calculated IK solution is sent directly through the network to the remote site, where the robot middleware processes such data and executes it on the robot.

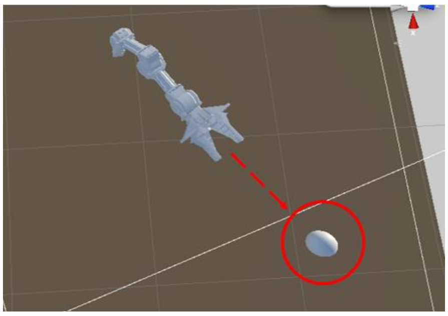

Fig. 5. The simulated robotic arm while following the VR tracker in Unity3d.

Remote site: we used OpenManipulator-X (RM-X52-TNM) [21] with an attached five-finger robot hand to perform physical manipulation tasks. The arm is controlled remotely by the user at the local site. The data is transmitted through the network from the local site to the remote site using WebSockets. Similar to previous works, we used a custom-made middleware to control each of the robot's servomotors through the network [22], [23].

C. The Robotic Hand

1) Hand Fabrication

We used a five-finger hand as an end-effector for our system to enable users to conduct various types of physical manipulations in a remote environment. The robot hand is based on youbionic hand [24] and was fabricated using 3D printed PLA parts with micro servo motors of type SG90 in each finger of the robotic hand. We attached force-sensitive resistors (FSR) to each finger to enable the tactile sensation of objects.

To control the robot hand, we used a Mini-Maestro 18-channel USB servo controller [25] and for feedback from the FSRs. Fig. 6 shows the final implementation of the robotic hand.

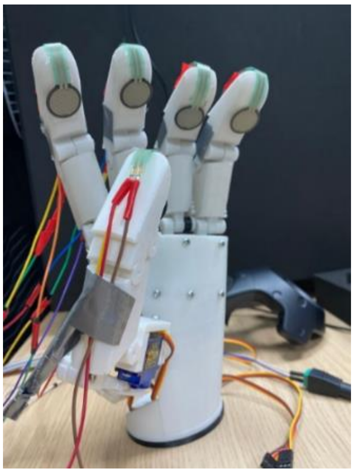

Fig. 6. The Robotic Hand.

2) Hand Control

Local site: to control the five-finger hand, we used Senso Glove [26], which enables five-finger tracking for the user's hands. We used the SDK for Unity3D to capture the user's hand postures using an IK model of the hand, The glove enables capturing 6 degrees of freedom, one for each finger and two for the thumb movements.

Upon reading the user's finger positions, the values are directly mapped to the PWM values of the micro servo motors. These values are then sent to the remote site to control the robotic hand through WebSockets.

Remote site: the same robotic hand middleware that was explained before was used for both executing the received servomotor values and reading the FSR values and sending them back to the local site.

3) The Haptic Feedback

Remote site: each finger on the robotic hand has a force-sensitive resistor (FSR) attached to it. Each FSR is connected to Pololu Maestro Mini [25], which is used to read the values of each. The read FSR values are then sent back to the local site to transform the data to haptic feedback using WebSockets.

Local site: after receiving the FSR data on the local site, we map the values into vibrotactile feedback values on the Senso Glove.

IV. AUGMENTATION THROUGH MOTION BLENDING

We set the objective of our proposed assistance system to enable users to reach and perform physical manipulations on objects of interest with high accuracy and with minimum effort. Overall, existing telexistence systems focus on high levels of embodiment, body ownership, and agency. Therefore, most control methods in telexistence systems are manual without introducing any assistance [3]. Accordingly, we implemented the Motion Blending algorithm to blend tracked user hand motion with system-generated motion when controlling the robot. Such assistance can be utilized for a variety of scenarios, such as in reaching, grasping, manipulating, or placing target objects at specific locations. Various levels of assistance can be chosen by the user, from minimal to high levels of assistance.

To achieve the above objective, we implemented our system to provide assistance during physical object manipulation through two main steps: A) Detecting objects of interest and sending their location to the local site. B) Augmenting User's movements based on desired Assistance Level. We explain each step below:

A. Detection and Localization of Objects of Interest at the Remote Site:

The system must locate the target object of interest within the remote environment. Such requirement is important for motion planning, generation, and executing the robot motions within the remote environment. To fulfill this requirement, we implemented a method for recognizing and localizing the object of interest in the remote environment, and then sending captured information to the local site (As shown in Fig. 7 below).

At the remote site, an Oak-D camera was integrated into the robot's workspace and placed in front of the robot's hand to be able to detect the target object and obtain its location with respect to the robot. We loaded the target object's detection model on the camera for detection, then returned the depth information of the objects to accurately localize it. We used an object detection model based on YOLOv4-Tiny [27]. For experimental purposes, the chosen target object was a cardboard cube (7.5 x 7.5 x 7.5 cm), however, other objects of various shapes or sizes can also be used.

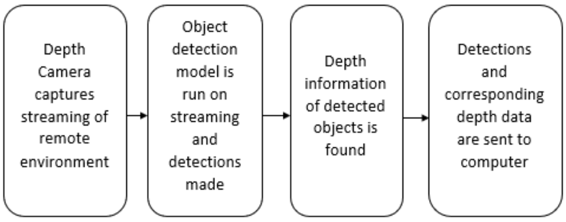

Fig. 7. Summary of process of detecting target object's position.

To train the model to detect our cube, a dataset of images of the cube was created using captured real-world images and synthetic images generated using Unity3D Perception [28]. The real-world images consisted of manually captured images of the cube and random images including negative samples (with no cube in sight). A total of 1144 images were in the final dataset, 1000 synthetic images, and 144 real-world images.

The dataset was split into 70% training and 30% testing data. Training of the YOLOv4-Tiny model was completed in a total of 1400 iterations over the training set. The model was then tested on the testing set. The achieved accuracy, precision, and recall were 98%. The trained YOLO model was then loaded onto the Oak-D camera with the use of DepthAI API for establishing communication with the camera and obtaining the detection bounding box information as well as the depth information of the detected target object in the hosting computer.

On running the Oak-D camera [29], the depth information of the target object from the camera's position is sent to the local site's control system. The data received at the local site is then transformed to provide the position of the cube in terms of the robotic arm's position within the Unity3D control system. This is then used to relocate a 3D model of the cube in the Unity3D environment to match the position of the cube in the real world.

B. Augmenting User's movements based on desired Assistance Level

The concept behind the motion blending algorithm is to give a different "weight" or importance to generate an IK solution that satisfies both objectives of following the user's hand position and reaching out to the cube's detected position. Therefore, the weight values determine how the IK solution is generated for following the target object's position and is blended with the IK solution for following the user's arm position. For example, assigning a higher weight for reaching the cube than following the user's hand position will cause the generated IK solution of the robot arm to incline more toward the cube's position than to follow the user's arms and vice versa.

Overall, the level of augmentation or assistance is defined by the range of weights given to both the cube's position and the user's arm position. The greater the weight values are given to the cube's position within the IK solver, the greater the level of assistance; as users need to move their hands minimally towards the cube as the blended IK solution inclines more toward reaching the cube's position than following precise movements of the users hands. However, with higher levels of assistance, the generated IK solution would be more autonomous and less controllable by the user.

In our system, we present users with 5 levels of assistance that determine the motion blending levels in the generated IK solution. The first level is one with no assistance, where the weight given to the user's tracked arm position is 100 and the weight given to the cube's position is 0. For the other 4 levels, the following equation was experimentally found to choose the specific weight to give to the cube's position at any instance while running the system. The weight is calculated in (1):

$$\begin{aligned} cubeWeight = {} & factor * WEIGHT\_CONST \\ & + difference * booster \end{aligned} \tag{1}$$

The WEIGHT_CONST is a value experimentally set to 100, and the factor is one of four values {0.5, 1, 1.5, 2} which, like the booster value, depends on the assistance level chosen. By multiplying the WEIGHT_CONST by the factor value, different minimum weight is set for every assistance level, between 50 and 200. To enable increasing the weight on the target object as the robotic arm gets closer to it, the second part of the equation is used. The "difference" is the inverted distance between the simulated robotic tip and the target object's position in Unity3D, which increases as the robotic arm moves closer to the target object. The booster value is one of four values {20, 40, 60, 80} which depends on the desired level of assistance. The booster value specifies a maximum value for the increase in the weight moving towards the target object. Multiplying the booster value with the difference allows the weight to increase gradually as the robot moves towards the target object. Finding the target object position weight allows generating an IK solution in the system to position the robot towards the target object. However, for augmentation, this weight is then used to find the weight to give to the user's arm position by subtracting it from a maximum weight set to 400. All the above values were experimentally chosen as they produced the best effect in our system.

The result of the calculations above is two different weights, one for the position of the user's arm, and one for the position of the target object. Assigning the weights in this way allows the blending of the IK solution generated for the arm position with the IK solution generated for the target object position. The final blended result is an IK solution that positions the robotic arm between the user's arm and the target object according to the weight assigned to each position as described above. The robot then moves according to the blended solution.

V. EVALUATION

A. Objectives

The objective of the study is to evaluate the effect of adding the haptic feedback module and assistance module on the user's ability to complete a task and their perceived body ownership of the system.

B. Participants

A total of 10 female participants were invited from the university to carry out the trials for each of the 4 phases of the evaluation.

Participants were aged between 20 and 22 years old (mean=20.9, sd=2.18), and they came from a variety of majors, with a majority being computer science majors. Only 1 participant indicated no previous VR experience, while the rest indicated they are quite familiar with VR. All participants indicated that they have not used telexistence or teleoperation systems through VR headsets before.

C. Conditions and apparatus

The conditions of our user study are as follows:

- Carrying out the task with no haptic feedback and no assistance
- Carrying out the task with haptic feedback but no assistance
- Carrying out the task with assistance but no haptic feedback
- Carrying out the task with assistance and haptic feedback

These conditions are used to test the following hypotheses:

- The presence of haptic feedback increases the sense of body ownership and improves interactions between the users and the remote environment
- The presence of assistance helps users to complete tasks with more confidence and control over the robotic arm.

To achieve our goal, the user on the local site will be wearing a VR headset and trackers, and Senso gloves to control the robotic arm, robotic hand, and head unit in the remote site to be able to accomplish the task.

D. Flow

We used a within-subject design, where all participants carried out all the experimental conditions in a random order to avoid potential learning effects. The experiment started with an introduction and a short familiarization session with each participant that lasted x minutes each condition consisted of three trials, where the user attempts to move the cube from its initial position to the destination with the same settings for the current phase.

After completing the three trials of each condition, participants took a body ownership questionnaire based on the Alpha IVBO questionnaire [30]. The questions are divided into three main components: Acceptance, Control, and Change. A 7-point Likert scale of 1 to 7; with 1 indicating "Strongly Disagree" to 7 indicating "Strongly Agree" was used for each question.

After completing all the conditions, we conducted a semi-structured interview where we asked users about their opinion and impressions about using our system.

VI. RESULTS AND ANALYSIS

A. IVBO Results and Analysis

We ran the repeated measures analysis of variance (ANOVA) test on the mean scores for the responses of each user per component of the IVBO questionnaire. The test was followed by pairwise comparisons with Bonferroni correction to find where the differences are among the conditions. Fig. 8 shows the mean score values for each component of the IVBO questionnaire from all the users' responses for each of the four conditions of the experiment.

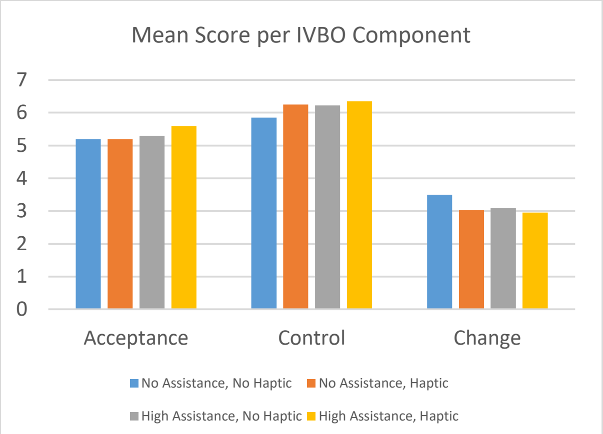

Fig. 8. The Mean score per component from participant responses to the IVBO questionnaire.

The significance value of F(3,27)=3.730, p=0.023 was observed for the control component of the IVBO. Fig. 9 shows the box plots for the responses of the users for the control component.

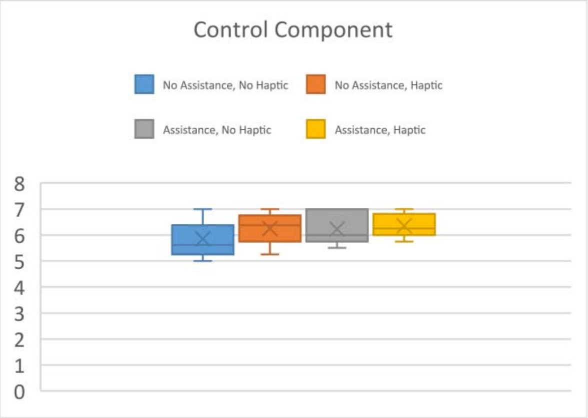

Fig. 9. The responses for Control Component per condition.

The main significance was observed between the first and third conditions, which were (No Haptic, No Assistance) condition and (No Haptic, High Assistance) condition, with a significance of p=0.01. This result suggests that participants mainly felt a difference in their control of the robotic arm with and without assistance when the haptic feedback was not turned on. Accordingly, we believe that the presence of haptic caused the participants not to feel the assistance very strongly.

For the other two components of the IVBO, there were no significant differences in the mean values for the results. Fig. 10 and Fig. 11 show the box plots for the responses of the users for the Acceptance and Change components respectively.

B. *Qualitative Results and Analysis*

In the semi-structured interview, the users were asked for general feedback about their preferences concerning the four conditions of the system. 70% of the participants found the condition with haptic feedback and assistance the easiest condition to complete, as shown in Fig. 12. This also matches the results of the ranking of the conditions from most preferred to least preferred, where 60% of the users preferred the haptic and assistance phase most and no haptic and no assistance phase least.

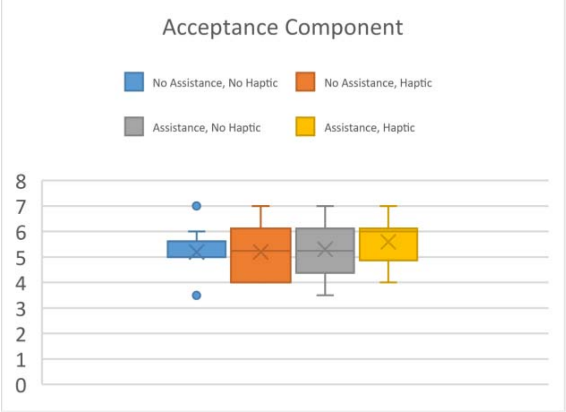

Fig. 10. The responses for Acceptance Component per condition.

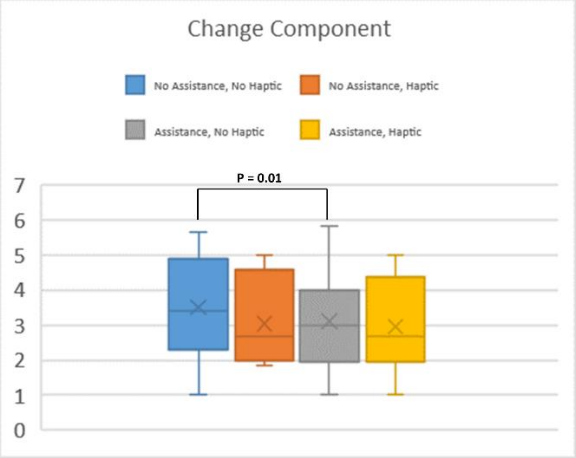

Fig. 11. The responses for Change Component per condition.

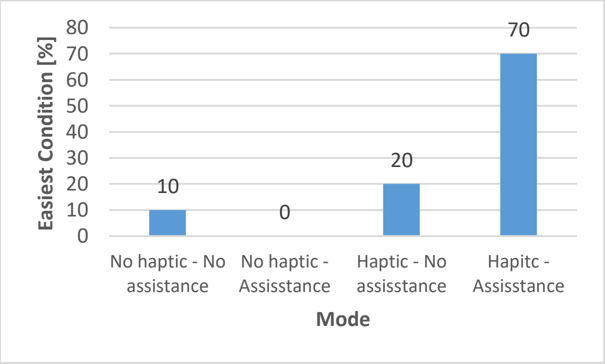

Fig. 12. The easiest condition results.

As for the general telexistence experience, users were asked about which feature they liked the most in the system. Around a third of the participants claimed that haptic feedback was their favorite feature. Also, in another question that asks to rate the usefulness of haptic feedback while holding the object, an average score of 6.1 out of 7 was obtained. Moreover, another 30% of the enjoyed the ability to move the robotic hand and that it copied their hands' gestures. The ability to move the robotic arm itself was also the most liked feature for 20% of the participants. The rest of the users found the ability to move the stereo camera by moving their heads the most enjoyable feature and it was generally a feature most users enjoyed using, as an average rating of 5.9 out of 7 was obtained when the participants were asked how much they liked moving the robotic head.

VII. DISCUSSION AND FUTURE WORK

By studying the results of each component of the IVBO questionnaire, the control component results indicate that the presence of the haptic feedback led users to not sense the provided assistance. This could be because of the assurance of holding the object that the user receives through the haptic feedback, which may distract them from concentrating on the arm movement. However, the lack of haptic feedback strips the users from that sense of assurance, thus making the user concentrate on the motion of the robot as their only means to ensure the successful completion of the task. On the other hand, the lack of significance between the two other conditions reflects how useful the presence of haptic feedback was on the user's ability to complete the task assigned. This corresponds to the responses collected from the interview question about how useful users perceived the haptic feedback for holding the objects, with an average score of 6.1 out of 7. Such results provide evidence indicating the haptic feedback's efficiency in improving the body ownership of the users.

Analyzing the results for the acceptance component matched the answers to the post-experiment interviews with regards to what they believed was the most difficult aspect when using our system, where 50% of the responses were related to moving the robotic arm in general. This could be because of shortcomings in the current robotic arm; the robotic hand's weight is relatively close to the maximum load that the arm can handle. As a result, users must move their arms to a greater distance to achieve the same motion required, which affected the extent to which they perceived the robotic arm as their own. As for the change component, the users generally completed each phase in around 3 minutes on average, before solving the IVBO questionnaire. As this is a very short time, users were unlikely to feel that their arms have changed much, which explains why even between the different phases, users did not perceive such a change.

VIII. CONCLUSION AND FUTURE WORK

This paper presents a motion blending method that maintains body ownership while potentially providing high levels of accuracy and assistance during remote telemanipulation. To realize our approach, we implemented a robotic arm with 4 DoFs with a 5-finger robotic hand that can be directly controlled by the user to perform various tasks. We also implemented hand controls and feedback using a haptic glove on the local site and FSRs mounted on the robot hand at the remote site. Our implemented motion assistance augments users' control of the robot by providing various levels of motion blending to assist users in conducting various tasks at different types of target objects.

Our evaluation performance showed that the presence of haptic feedback and assistance enhanced the telexistence experience. The majority of the participants in the evaluation process found the assigned tasks easier to complete with these two settings activated. It was also found that the presence of assistance supported and strengthened the user's sense of control over the robotic arm, especially when the haptic feedback was not activated.

For future work, an evaluation of the system could study the effect of the different levels of assistance beyond what we have implemented. Moreover, the user studies should be expanded to involve more varied types of users and more complicated tasks. We believe that novelty of our approach to assisting user's controls is one step toward a more effective telexistence that does not jeopardize the sense of agency, body ownership, or task success.

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