WFH-VR: Teleoperating a Robot Arm to set a Dining Table across the Globe via Virtual Reality

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Abstract— **This paper presents an easy-to-deploy, virtual reality-based teleoperation system for controlling a robot arm. The proposed system is based on a consumer-grade virtual reality device (Oculus Quest 2) with a low-cost robot arm (a LoCoBot) to allow easy replication and set up. The proposed Work-from-Home Virtual Reality (WFH-VR) system allows the user to feel an intimate connection with the real remote robot arm. Virtual representations of the robot and objects to be manipulated in the real-world are presented in VR by streaming data pertaining to orientation and poses. The user studies suggest that 1) the proposed telerobotic system is effective under conditions both with and without network latency, whereas a method that simply streams video does not. This design enables the system implemented at an arbitrary distance from the actual work site. 2) The proposed system allows novices to perform manipulation tasks requiring higher dexterity than traditional keyboard controls can support, such as setting tableware. All results, hardware settings, and questionnaire feedback can be obtained at https://arg-nctu.github.io/projects/vr-robot-arm.html.**

I. INTRODUCTION

The COVID-19 epidemic has prompted many people to work remotely from home in order to avoid in-person exposure at the work site. Nonetheless, many tasks requiring specialized skills and experience cannot be autonomously executed by robots reliably under real-world uncertainty. Teleoperation solutions are helpful in these situations [1], [2]; however, the conventional approach using a 2D interface can be very cumbersome [3], particularly when operators are required to manage their views of the scene and command robot actuators using a keyboard and/or mouse [4]. Recent advances in VR devices have made it far easier to work remotely by immersing operators in a higher-fidelity virtual environment.

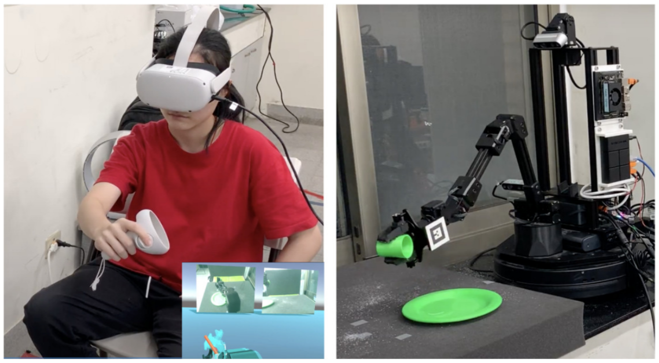

Fig. 1. A user controls a LoCoBot remotely to set up a dining table via virtual reality.

In the current study, we employed a consumer-grade VR device (Oculus Quest 2) in fabricating an user-friendly virtual reality-based teleoperation system for controlling a low-cost robot arm (LoCoBot). LoCoBots are commonly available and can be deployed at scale. As shown in Fig. 2, the user obtains visual feedback through a VR headset. The user assigns the desired location for the end point of the robot simply by manipulating a VR controller. The VR interface includes a real-time image feed as well as its virtual counterpart, which is composed of 3D models. The two images are linked to the movement of the robot within the context of the surrounding area. Virtual counterparts are generated by estimating the pose of actual objects via deep object pose estimation (DOPE). Thus, even when the actual objects are partially occluded, the entire shape of the virtual counterpart can be seen in VR. This makes it easier for the user to operate the robot arm and interact with objects, while checking the state of the actual object via camera feeds. Our interface can display not only the real robot state (black robot arm in Fig. 2) but also the commands of the end point via the user's VR controller (transparent virtual fixture in Fig. 2). Besides, pressing the button on the VR controller can deliver the commands to the real robot. The two main movement functions (opening/closing the gripper, and moving the effector) only track the user's motions when a specific button is pressed, in order to eliminate unintentional movements of the robot. Further, through transparent virtual fixture, the user can practice and pre-see what the robot arm will do before making the orders.

The proposed virtual fixture/robot arm is meant to give the operator insight into the means by which the system will respond to commands [5]. A priori information pertaining to the system or task makes it possible for the operator to share control. We made it possible for transparent virtual representations to pass directly through virtual objects with the aim of reducing the mental processing required for remote tasks, while minimizing reliance on sensors without compromising the high precision of robotic systems, which are expected to match or exceed the natural ability of humans. The system developed in this study employs shared

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control, in which the movement of the virtual robot arm is based on the commands pertaining to multiple joints (i.e., the inverse kinematic approach) with the actual state of the joints presented to the user in VR. Note that our system uses virtual objects in addition to a virtual robot arm. The pose of a virtual object is derived from the actual object using deep object pose estimation (DOPE) based on a single camera. In situations where the pose of the actual object is unavailable (e.g., temporary communication issues), a physical engine simulates the dynamics of the objects with the aim of preserving interactions until the pose is updated using data from the actual object. Compared to systems based on streaming video, our use of virtual objects requires far less data (only positions and attitudes), thereby minimizing latency imposed by data transmission.

There has been significant attention and competition [6] with regard to service robots' grasping and manipulation tasks, such as setting up a dining table. Through virtual reality, our users controlled a robot arm to arrange tableware (e.g., plates, forks) to match target positions and to perform tasks (e.g., pouring water). We recorded the time for performing different tasks and the users' feedback about using our system. The functionality of the system was assessed in user studies involving participants with no previous experience performing such operations. The major contributions of this work include the following:

- **Effectiveness of visualization methods under reduced frame rate**. The proposed VR robot teleoperation system, in which 3D virtual counterparts and virtual fixtures are presented via a virtual interface, was found effective against decreased frame rate compared to video stream visualization methods. Different manipulation strategies adopted by different participants are analyzed.
- **Efficacy of VR for the group with/without previous demonstration vs. conventional keyboard control methods**. We evaluate the VR robot teleoperation system using different dining table tasks and comparing it with alternative approaches keyboard control via a 2D screen.
- **Evaluation of how long it takes to master the teleoperation for novice participants**. The efficacy of the proposed system was demonstrated in a user study involving novice participants.

II. RELATED WORK

A. Telerobotics

Teleoperation by a human operator is often the only practical alternative when dealing with grasping and manipulation tasks that are too specific for autonomous solutions [4]. Telerobotic systems implement commands and relay information back to the operator. Control architectures can be classified as (1) direct control, (2) supervisory control, and (3) shared control [7]. Direct control implies that all slave operations are controlled directly by the user via a master interface, such that the system does not require innate intelligence or the ability to operate autonomously. Supervisory control implies a sparse connection between the user and a largely autonomous telerobot. In these systems, the operator sends only high-level commands, and the telerobot refines the tasks autonomously. One approach to supervisory control involves telesensor programming [8], in which robot tasks comprise elementary moves representing different subtasks described by the initial and final states. The transition from one subtask to the next subtask (i.e. the recognition that the goal state of the elemental move has been reached) is performed heuristically. Shared control implies that in the execution of a task, the commands are shared by the operator (direct control) and the robot (local autonomy).

Virtual reality (VR) provides an interface that allows users to specify points and transforms in an intuitive manner, but any communication with a remote system involves a signal delay, particularly in systems that depend on sensors. Telerobotic systems that suffer from significant latency tend to benefit from sensor-based programming ; however, this type of coarse planning does not allow for fluid interactions and precludes the performance of delicate tasks by non-experts. This work can be categorized as shared control. Some researchers have investigated recreating the remote environment with stimulated time delay model. By using Augmented reality to allow a operator to teach and operate a robot arm to do manipulation tasks. [9]. In our user studies are carried out at a real network connection to examine the effects of the poor network connection on novice/expert participants.

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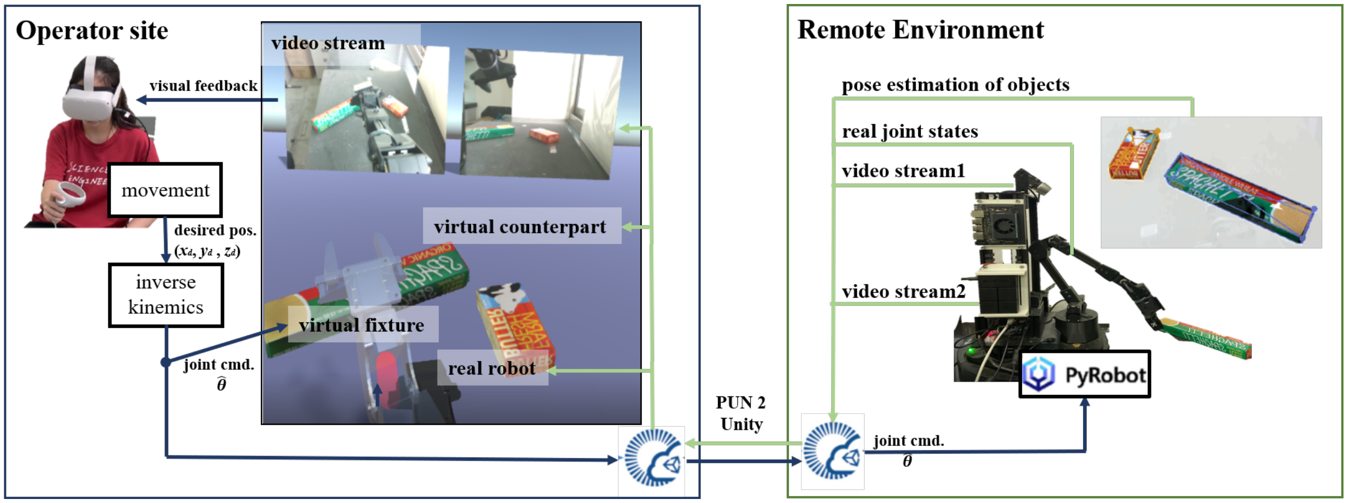

Fig. 2. System architecture of VR-based teleoperation system, which can be operated over the internet from anywhere in the world. In addition to the two real-time image feeds, virtual representations reflect the means by which users naturally interact with a target. Translucent virtual representations are used to indicate the predicted state of the robot after it receives a command.

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B. VR Teleoperation

Intuitive interaction is the cornerstone of efficient task execution in teleoperations. However, most conventional teleoperation schemes rely on computer monitors and joysticks or keyboards to actuate the robot. These 2D interfaces are cumbersome and workload-intensive (i.e., they require significant mental effort) [3], [4]. Utilizing VR in robotic systems involves the direct mapping of VR hand controllers to robot manipulators via an interface [10]. Another approaches are building up exoskeleton for the operator to teleoperate bimanual robotic avatar [11], [12], [13] or using motion capturing system to teleoperate a aerial manipulator [14] and a hyper-redundant robot [15]. High-fidelity graphic renderings and native changes in viewpoint can assist in planning robot motions and overcoming the limitations of 2D interfaces. Researchers have proposed mobile-robot teleoperations aimed at validating the functionality of immersive VR environments [16], [17], [18], [19], [20], [21]. In most previous studies, human following and motion planning are implemented separately, with the primary focus on the effects of latency on the synchronization and positioning of targets in the real world and those represented in the VR system. When performing tasks that involve dexterity, robots generally perform multiple pick-up-and-place tasks. [22], [23]

In dealing with the distance between the gripper and object, some researchers have employed a wrist camera by which to read a range sensor and project a stereoscopic view of the arm [10]. Images from the camera can also be linked to a hand controller to enable constant monitoring during manipulation [3]. Despite limited success in the performance of VR tasks, it should be noted that the streaming of camera images via VR remains a special application of 2D interfaces. One approach to building virtual objects in VR involves tag recognition for the localization and tracking of objects relative to the robot itself [3]. Nonetheless, affixing tags to objects is difficult in many industrial applications. It is possible to build virtual objects by rendering color 3D point cloud from a remote depth camera mounted on the wrist [19], [22], [24], [25], [26], [27]. Some researchers have improved transferring large amount of 3D point-cloud led to a burden over network, they proposed an automated object detection and streamlined data transfer method. The system executes the classification and segmentation algorithm. The raw point cloud data is then replaced by virtual objects to reduce the amount of transferred data [22], [23]; however, the target object is often occluded by the robot arm. In the current study, we employed DOPE in our VR interface to ensure that all of the contours and textures of virtual objects can be displayed in VR.

III. PLATFORM DESCRIPTION

Figure 2 presents an overview of the proposed approach in which the user and physical robot are separated by an arbitrary distance (online mode). The proposed system comprises two operations: controlling the robot arm and synchronizing virtual objects with real-world objects. We employed Unity PUN2 for all communication tasks over the internet and an Oculus Quest 2 VR headset to visualize the virtual environment while manipulating the robot arm. Within the virtual environment, real-world objects are replicated via 3D reconstruction or CAD modeling. The actual robot arm and gripper are controlled by guiding an identical virtual robot arm (i.e., an arm with the same joint configuration and dimensions as the real arm). These movements are synchronized for both the VR user (client) and the physical robot's environment (host) in the virtual scene. The interface also provides a video signal streamed from the workplace via Unity PUN2.

Based on the position of the virtual robot's end effector, our system computes the state of the virtual robot arm joints, which are then (upon confirmation by the client) published to a physical Rosbridge server by the host to update orientation data pertaining to the actual robot arm. Virtual objects are synchronized with real-world objects by continuously performing pose estimation using Deep Object Pose Estimation (DOPE) [28] to process RGB images captured using a camera attached to the base of the actual robot. DOPE is used to estimate the pose parameters (position and orientation) of real-world objects in order to update the virtual objects.

The proposed system enables users to observe virtual scenes that are synchronized with corresponding real-world objects in the physical workplace, and to remotely control the robot arm. Note that very little data is required for transmission (robot orientation, object poses), thereby minimizing latency to make manipulation more intuitive.

A. Hardware

The proposed teleoperation platform was implemented using a consumer-grade VR device (Oculus Quest 2; $420) and a low-cost robot (LoCoBot; $5,000). The Oculus Quest 2 system provides a head-mounted display comprising a singular fast switching LCD panel with a resolution of 1832 × 1920 per eye and a refresh rate of 120 Hz. It is also equipped with two Oculus Touch hand controllers with 6 DoF pose tracking using infrared LEDs, thereby allowing comprehensive tracking in a 3D space by the Oculus Quest 2 constellation system. Figure 2 presents the LoCoBot robot used in this study with a control system comprising the following components: an Intel RealSense RGB-D Camera D435, a Jetson Xavier NX, a WidowX 200 Mobile Arm (5 DOF), an Intel NUC, and a Kobuki Base. In addition to the original camera at the top of the robot, we attached an Intel RealSense RGB-D Camera D435 near the base of the arm to capture RGB images for object pose estimation. Note that we opted not to use the original camera due to the likelihood of robot arm occlusions, which could cause pose estimation failures. The teleoperation system was developed in Unity, a 3D game engine that supports major VR headsets, including the Oculus Quest 2.

B. Pose Estimation

Numerous researchers have applied deep neural networks to the task of 3D object detection and pose estimation. Tremblay et al. [29] introduced the deep object pose estimation (DOPE)[28] method to facilitate the grasping of household objects by robots. Our proposed system uses DOPE as well, but not for grasping. Rather, DOPE is used to estimate object poses on the robot side in order to update the poses of virtual objects on the VR side with the aim of synchronizing the actual working environment with the virtual working environment. As shown in Fig. 3, the LoCoBot was equipped with two cameras (at the top and bottom right of the base), both of which can be used as a ground-truth source for position and orientation at any given moment. The top camera was used for real-time image streaming, whereas the lateral camera was used to capture images with which to estimate objects' poses. The robot was also equipped with an NUC computer, which was responsible for communication tasks between the robot, the Unity system, and Xavier NX in performing DOPE calculations. The NUC was connected to a Rosbridge Master IP, an open-source program that converts JSON API to ROS functionality. The Unity program used the ROS# package, which is an open-source software library with tools written in C# for communicating with ROS via .NET applications, connecting with the ROS Master IP, and listening to topics related to image streaming and object orientation. We employed the popular YCB object model as a reference to facilitate the rendering of objects (e.g., a Domino sugar box).

C. Robot Arm Control in Virtual Reality

1) Visual Interface: Effective control over the robot in virtual reality requires the user to have a clear spatial understanding of the environment to be manipulated on the robot's side. After Unity receives an object's position and orientation data from DOPE via the local Rosbridge connection with the robot, it synchronizes the virtual object's orientation with the real-world setting. Nonetheless, self-occlusion often occurs when the robot arm is picking up an object, in which case DOPE[28] may fail to estimate the object's pose. To mitigate this problem, the object in this situation is rendered as slightly transparent, to let the user know that the object's pose is uncertain. Further guidance is provided by streaming RGB video signal from the top camera to a designated screen in the virtual working environment. This is intended to clarify the positions of objects and events at the work site to the user. We employed the open-source LoCoBot's URDF model by Trossen Robotics to recreate the virtual robot model inside Unity: one model for orientation synchronization with the real robot arm (opaque) and another one for synchronization with the user's movement (transparent) as shown in Fig. 2. The user guides the virtual robot arm (in VR) before confirming the desired positions and orientations of the joints. The position and orientation of the Oculus Quest right controller are mapped onto the transparency model of the virtual robot arm, thereby allowing the user to move their arm freely, while guiding the movement of the virtual robot arm with the action visualized in real time.

2) Control Interface: To minimize communication latency and avoid severe computational expense on the robot side, we replaced the PyRobot inverse kinematic solver with Unity's kinematic chain and IK solver to compute the positions and orientations of the physical robot's joints based on the end effector of the virtual LoCoBot. Once the positions and constraints have been set, the FABRIK algorithm [30] is used to compute the movement of the joints based on the position and orientation of the end effector of the virtual robot, which is mapped onto the right controller. The user then confirms the desired position and orientation by pressing the grip button on the right controller, whereupon the host's Unity program publishes the joint coordinates of the virtual robot to the local Rosbridge server via ROS#. This triggers

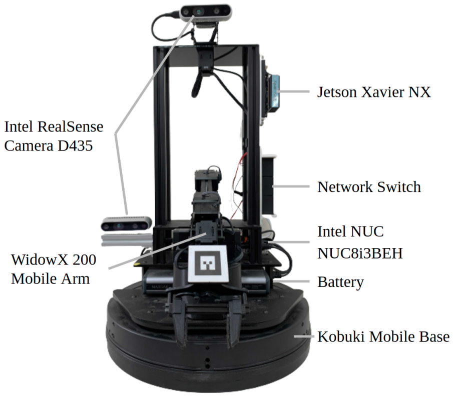


Fig. 3. The proposed robot setup.

a handler script to read the virtual joint topic and uses PyRobot API [31] at the NUC to accurately set the joints of the physical robot arm. By circumventing PyRobot IK, this approach avoids the computation latency that it would otherwise impose, thereby making it possible to control the real robot in real time when a movement is performed by the user.

D. Network Control

Photon Unity Network 2 (PUN2) is a real-time cloud framework used to host online multiplayer games for Unity developers. We leverage the Remote Procedure Calls Protocol (RPC) of PUN2 to send and receive data remotely and synchronize the virtual scene with minimum latency. Here, the VR user (client) sends their controller inputs and coordinates after IK calculation to the robot (host) via RPC, for use in adjusting the robot's position. Accordingly, the video streams and object poses (estimated by DOPE)[28] are sent from the host to the VR side for synchronizing the virtual working space with the real-world environment. Because only the robot side needs to be connected to its local Rosbridge server, the client can control the robot from any location that has access to the internet. We found that there is no significant delay (i.e., longer than 1 second) from the synchronization of the real robot state to VR and the virtual robot state from client to host. However, video streaming and virtual counterparts suffer from frame rate reduction, from 14 fps and 1.4 fps accordingly to 0.75 fps for all methods; this is largely due to the bandwidth limit imposed by PUN and internet connection speed. Note that significant latency only exists in online control mode. With offline control using a LAN connection, the latency can be safely ignored (less than 1 second).

We investigated the user experience of teleoperating a robot arm to set a dining table. The two ends of the experiment were set in two universities located halfway around the world. Specifically, the VR side was set up at George Mason University in Virginia, US, and the actual robot was set up at National Yang Ming Chiao Tung University in Taiwan. Each user was instructed to pick up a box and place it in a specific position. The user was able to observe a virtual box and a virtual robot arm resembling the actual box and robot arm. A video stream showing what was happening on the robot side was also streamed to a virtual screen in the virtual working environment.

IV. Human-robot-interaction Experiments

The effectiveness of the proposed system in remote teleoperation tasks was evaluated by conducting a user study involving three experiments. All of the participants (ages 20-40) lacked any prior experience with our platform. Experiment 1 focused on the visualization methods used in the proposed system, including video (in the form of a 2D monitor interface) and the virtual counterpart (rendered via pose estimation). Experiment 2 focused on evaluating how well our proposed system allows even novices to perform tasks of high dexterity. In accordance with the Robotic Grasping and Manipulation Competition at IROS 2021 [32], we employed 5 tasks involving setting a table. The final experiment focused on mapping the skills developed in one task to another task. The setups of the experiments are shown in Fig. 4. In addition, the results of a 7-point Likert scale were used for subjective analysis, and the number of failures to complete a task was used as an objective index of difficulty.

A. Experiment 1: Methods of Visualization

The first manipulation task involved pushing one object and then stacking another object on it. Both of the objects used in this experiment were selected from the YCB object set. The objects were visualized in VR using (a) one real-time image, (b) two real-time images from different perspectives, or (c) virtual counterparts rendered via pose estimation.

A local network was set up via a wired Ethernet cable connection between the computing unit of the LoCoBot and the desktop in the remote environment, and the Oculus Quest 2 was connected via a USB cable to the desktop in the operator site. We first conducted a test under two different network modes: 1) Local mode (without PUN2 but with Rosbridge) and 2) Global mode (with PUN2 and Rosbridge) by changing gripper state and going a list of designated goal pointsto estimate latency. The method here was for all computing units to do the time synchronization with the public time sever at the beginning. Then, when the button was triggered by the user, the current UTC date-time was recorded and a ”trigger message” was passed though the internet to the remote side. Once the message was received, a ”feedback message” was sent back to the operator side immediately, and the current UTC date-time on the remote side was recorded. The difference between these two times was considered the communication time. We assume that the communication time is the same as the update time of virtual robot arm. Based on the recorded video, we collected the real update time from video streaming when the desired state was updated. For Local mode, the test was performed by a VR user in the same building as the LoCoBot. In this setting, the communication time was approximately 0.03 seconds, and the real update time was approximately 0.1 seconds. By contrast, for Global mode, the test was performed by a VR

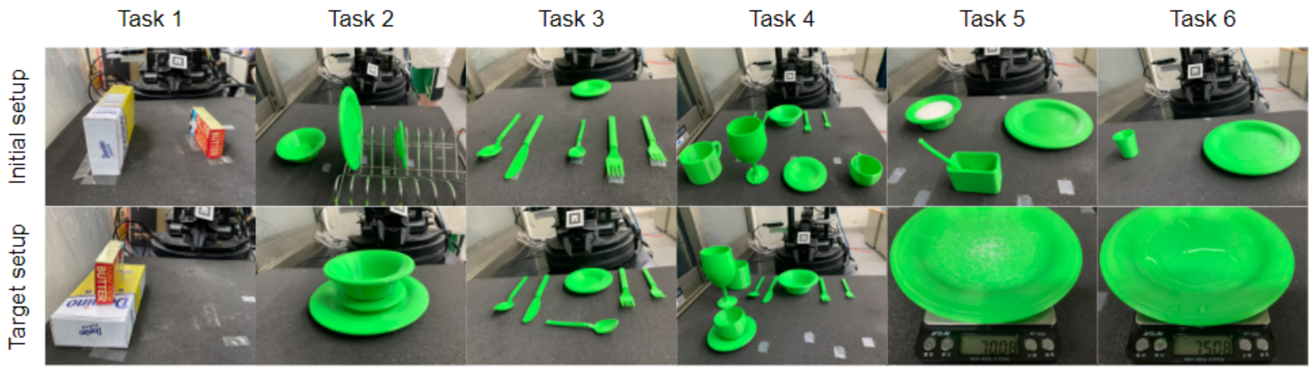
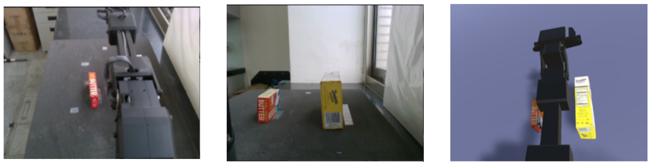


Fig. 4. We evaluated our system based on dining table setting tasks, including: (1) pushing and stacking of boxes; (2) picking up and stacking plates and bowls ; (3) picking up and placing multiple implements such as cutlery; (4) rearranging glasses and cups ; (5) smoothly scooping sugar grains from a set distance; (6) smoothly pouring water from a set distance. The proposed system allows even novices to perform tasks of high dexterity through the remote manipulation of a robot arm via the internet from anywhere in the world.

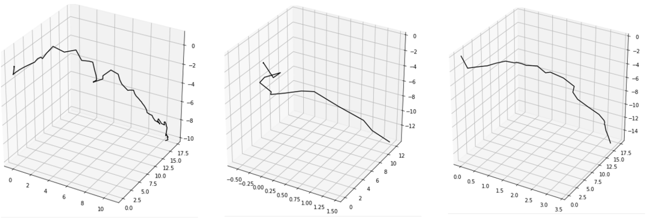


(a) top camera

(b) lateral camera

(c) virtual counterpart

Fig. 5. Initial views of different visualization methods. Method (a), one-image stream, includes only the image top camera. Although the objects were almost occluded, information about the location of the robotarm relative to the objects could still be provided. Method (b), two-image stream, includes images from both the top camera and the lateral camera, providing the user with a more comprehensive view of the work space. Method (c), virtual counterparts, generates the whole object model in VR, including partially occluded real objects via only the lateral camera.



(a) trajectory via method (a)

(b) trajectory via method (b)

(c) trajectory via method (c)

Fig. 6. The trajectories of a reference point (gripper_link relative to the base_link of the LoCoBot) from the initial position until the first moment of contact against the yellow box via all visualization methods performed by an expert. (unit: cm) (a) The strategy for overcoming the occlusion by moving the robot arms several times manifests in the jagged line in the trajectory plot. (b) With 2 different perspectives, the trajectory became smoother. (c) Virtual counterparts allowed the expert user to complete the task directly and quickly.

user in the US while the robot remained in Taiwan. In this setting, the communication was approximately 0.35 seconds and the real update time was approximately 0.2 seconds. This indicated that less than 0.2 seconds for Local mode and 0.6 seconds for Global mode will work properly with our system. In addition to the latency discussed here, we will also discuss how decreased frame rate will affect the participants' performance.

To compare the various approaches to visualization, we recruited 12 participants who were novices in the use of VR systems (i.e., with 5 or fewer hours of experience). We also decreased the frame rate (originally 14 fps from the camera feed and 1.4 fps for the virtual counterparts) to 1 fps (for all methods) in order to simulate the frame loss one would expect to encounter when using a poor network connection. Each time a participant was unable to complete a task, they were free to ask for help in repeating the task. Half of the participants manipulated the robot using the video stream first (a and b) and then using virtual counterparts (c). The other half of the participants performed this sequence of operations in the opposite order. Fig. 7 displays the average completion time, which was used to quantify the efficiency of the methods. In terms of completion time, the use of virtual counterparts proved most helpful. The use of virtual counterparts minimized the degree of variance in the outcomes as well as the number of task failures, regardless of the frame rate, such that most of the participants were able to complete the task in their first try. Note that under a lower frame rate, the average time top completion was slightly longer (> 5s) than under a normal frame rate. Even though the distance of the field was provided positional information like binocular vision in Method (b), the participants preferred to use the virtual counterpart, regardless of latency. When using Method (b) with a lower frame rate, the participants expressed that they felt uncoordinated. Taken together, these results reveal that a virtual model based on pose estimation facilitates robot manipulation, even when operated on a poor network. Furthermore, the user's strategy depended on the visualization method applied. All methods were each performed once by an expert (> 20 hours operating VR systems). Fig. 6 shows the trajectories were drawn by a reference point (gripper_link relative to the base_link of the LoCoBot) from the initial position until the first moment of contact against the yellow box in Fig. 5. As shown in Fig. 5(a), the robot arm initially appeared in the view from the top camera; however, both of the objects were nearly occluded by the robot arm. The strategy used in implementing this task can be derived from overcoming the occlusion by moving the robot arm several times, as depicted by the jagged lines in the trajectory plot. Hence, it took the most time among these 3 methods. Method (b) provides

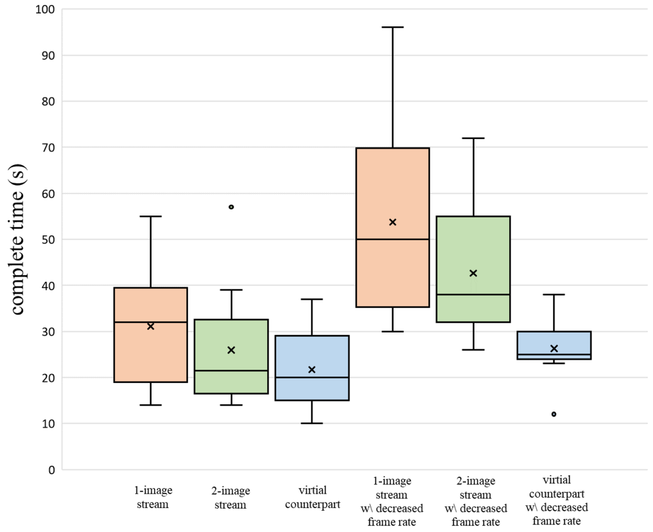


Fig. 7. Completion times obtained via various visualization methods using normal frame rate and decreased frame rate.

TABLE I

We recruited a total number of 28 participants to conduct the 5 tasks. The benchmark results of average score and time spent in each task are shown.

N of Participants	KM-Expert 1	VR-Novice-B 10	VR-Novice-A 18	VR-Expert 1
Completion Time (unit: s)				
1: plates/bowl	197.3	139.6	133	102.8
2: tablewares	143.5	135.5	135.7	92.7
3: glasses/cups	260.8	169.3	161.4	110.8
4: sugar	86.3	156.1	58*	50.5
5: liquid	57.8	69.4	44.4	47
Score (unit: pts)				
1: (120) plates/bowl	112	100	108.89	110
2: (300) tablewares	276	271	255.56	282
3: (70) glasses/cups	66	66	67.5	70
4: (50) sugar	25	37.5	44.44*	50
5: (50) liquid	25	30	41.67	50

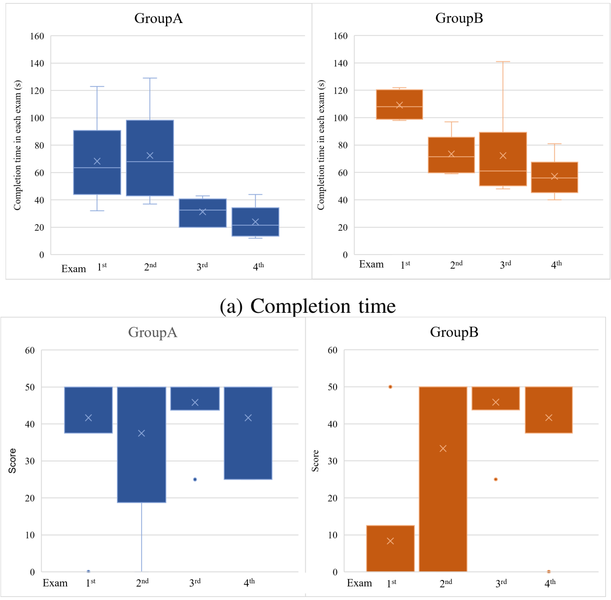
* The participants in this group only had one chance to transport sugar grains, whereas the other groups could attempt the task repeatedly until they wished to stop.

the other perspective from the lateral camera, which clearly shows the objects, but the robot arm was out of the view of this camera in the initial state. The user cannot determine the location of the robot arm relative to the objects only by lateral camera in the beginning; hence, the combination of top and lateral camera is necessary for having whole scenes like binocular vision. Compared to the trajectory in Fig. 6(a), the trajectory via Method (b) was smoother. As for the virtual counterpart from the lateral camera, it allowed the expert user to complete the task directly and quickly. This can be attributed to the fact that DOPE[28] was able to generate virtual counterparts of partially occluded objects. Hence, the expert user was able to benefit for interactions with the object. Based on the above the experimental results and the trajectory, Method (c), virtual counterpart, was user-friendly and promising for both novices and expert users.

B. Experiment 2: VR vs. Keyboard Controls and Task Performance Benchmark by User Groups

The experiment tasks are inspired by the multi-year IROS Robotic Grasping and Manipulation Competition - Service Robot Track. The objects we used in the experiments are also inspired by the YCB objects and common objects on a dining table. Due to the hardware payload and gripper limitations, we chose to scale down the objects by modeling CAD models followed by 3D printing. Such modifications also considered easy replication of our work using LoCoBot hardware. All CAD models will be publicly available. There were other tasks designed in the competition, but we found them infeasible for the LoCoBot setup, such as the ice cubes task (which requires touch sensing) and the sugar packet task (which requires dual arms). Figure 4 depicts the five tasks (2-6). We chose a range of tasks and modified them to fit with our robot setup.

We recruited 28 novices to use our VR teleoperation system for the 5 tasks feasible for our hardware setup. All participants were first-time users. After some instruction, the participants wore the VR head mount and used the hand controller to interact with the objects. They were not instructed to grasp the objects in a specific way, and therefore all possible motion primitives, such as pushing, grasping, and placing, were allowed. In Tasks 2 to 4, there was a 5-minute time limit for each task, but there was no limit in terms of number of attempts made within that time constraint. In Task 6, users were only allowed one attempt to transport the fully-filled water cup. We also reported a baseline using keyboard and monitor (KM) inputs by a researcher experienced with our VR teleoperation system, to perform 5 trials of each task. We evaluated performance by counting the scores following the rules in the 2021 competition. Group A (18 novices) were given some tips and allowed to watch previous participants before starting each task. Each participant in group A performed 2-3 trials with different tasks. Group B (10 novices) was a control group that did not receive any instruction. Each participant in group B performed 1 trial for each task. In total, 50 trials and 44 trials evenly distributed for each task were collected. Table I shows the average scores and completion time of using a VR video stream and controller (VR-VS) versus keyboard and monitor (KM). Overall, both VR-VS and KM methods were able to complete all tasks. However, the execution time for VR-VS was shorter than that by KM. We observed that the VR interface allows different **motion primitives** like pushing or fine-tuned adjustment of the positions or orientations of the knife and fork. This affords the user multiple strategies to fine-tune incorrect motions, such as a poorly aligned pick-up-and-place maneuver. VR showed superior performance in Task 5 and Task 6 than KM by better **fluency in 6 DoF grasping**. During transport, the sugar grains or water tended to drop or splash out when controlled by KM due to a sequence of noncontinuous strokes. Using VR led to smoother and more intuitive control than KM. VR was also useful in Task 5; as the spoon reached into the sugar grain container, the scooping required **dexterous manipulation** to successfully retrieve the desired amount of sugar grains. Such skills were difficult to perform using the KM method. Note that the sequence of actions to perform the Task 6 appears



(a) Completion time

(b) Score

Fig. 8. The completion times and the scores of Group A (with practice) and Group B (without practice) in each exam.

TABLE II
THE COMPETITION TIME, SCORE AND P-VALUE BETWEEN GROUPA AND GROUP B IN EACH EXAM.

	Competition time (s)			Score		
	p-val	mean(A)	mean(B)	p-val	mean(A)	mean(B)
E1	0.358	96.7	109.2	**0.009**	**41.7**	**8.3**
E2	0.474	72.5	73.5	0.383	37.5	33.3
E3	**0.010**	**31.3**	**72.3**	0.500	45.5	45.8
E4	**0.001**	**24.0**	**57.2**	0.500	41.7	41.7

*p-val: p-value
mean(A): the mean value among GroupA
mean(B): the mean value among GroupB

simple, but is in fact far more difficult than the other tasks for the novices. For example, if the cup is not tilted rapidly to pour out the water, then most of the water falls diagonally (hanging onto the cup's outer wall) rather than falling vertically. However, our results do not provide evidence that an opening expert demonstration improved participants' performance on 5 tasks. From the background investigation, the participants in group B were all inexperienced with VR but experienced with robotics, whereas the participants in group A, 15 having VR experience and 4 having robotics experience. We discovered that the participants with VR experience, who are familiar with hand controllers, perform dexterous manipulation more proficiently than Group B. Nevertheless, we find that our proposed system allows even novices to perform tasks of high dexterity. We further explore how the novice to become expert in the next experiment.

C. Experiment 3: Practice Makes Perfect

We conjecture that practice will make perfect, but how long does it take, and what kinds of practice could best allow a novice to master teleoperation? An experiment involving both practice and exams was set up to investigate. Task 6, pouring water on a plate, was selected for this experiment because previous experiments observed that tasks of this type require dexterous skills for teleportation. We grouped 12 novices into GroupA (with practice) and GroupB (without practice). This task, taken as the exam, was executed 4 times for each participant. The main difference was that GroupA did the practice before every exam. During the practice, GroupA operated the gripper to (1) approach a yellow box (the same box as in Task 1) 3 times, but not pick it up, for 3 minutes, and (2) draw the trajectory in the air with the box in hand for 1 minute. On the other hand, Group B simply rested for 4 minutes. It should be mentioned that the motion primitives during the practice were different from the exam. The results are displayed in Fig. 8. The performances of all participants had significantly improved. They completed the task in shorter time, and get higher scores. On the 4th exam, all participants in GroupA completed the task in less than 45s, a performance very similar to the expert user (44s). Almost all participants in GroupA highly agreed that they felt more confident in the exam after doing several practices (average: 6.5/7), and found that practice was helpful for mapping the skills from practice to the exams (average: 6.5/7). As for GroupB, although the average scores in the last 2 exams were similar to GroupA, the average completion times were much higher (>30s). Which implied that the participants spent more time would perform better. GroupA with practice felt more confident for the exams; hence, they tended to spend less time and getting good-enough scores. In summary, it took a predictable time to make a novice have an expected performance. Furthermore, performing similar motion primitives was helpful for dexterous manipulation.

V. CONCLUSION

Our paper presents a novel approach to the VR teleoperation of a robot arm. Our toolkit will be released for free to facilitate adoption and future extension. Current limitations and possible extensions include the following: a) pose estimation failures due to self-occlusion, which could be addressed through the use of additional cameras; b) limited flexibility due to the use of only one robot arm with a gripper hand, which could be addressed by using an additional arm and a five-finger hand for performing more sophisticated manipulations; and c) failure to consider deformable objects (e.g., clothes), which may be addressed by estimating the 3D geometry of objects in real time.

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