# Advancing Collaborative Research in Communication and Robotics: Insights from Experiments in a Remote Experience Center

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***Abstract*—The rapid evolution of 5G and the emergence of 6G mobile networks unlock transformative possibilities for collaborative robotics, with a particular emphasis on teleoperation systems that demand high-quality, low-latency communication. However, progress in teleoperation and communication remains fragmented, as researchers in these fields often lack interdisciplinary expertise and access to essential experimental infrastructure, including advanced robotic platforms and 5G/6G testbeds. The interdisciplinary expertise and infrastructure gap hinder the cross-disciplinary collaboration required to advance collaborative robotics using next-generation networks. In this paper, we introduce the concept of a Remote Experience Center to address this gap, demonstrating its implementation through a teleoperation framework that integrates a software-defined mobile network deployed in Prague with a robotic platform situated in Munich. We perform two classical teleoperation tasks, pick-and-place and peg-in-hole, transmitting robot control signals, as well as visual and force feedback, over the software-defined mobile network in Prague to a robotic platform and human operator located in Munich. To enhance research safety and ensure broader accessibility to our framework, we also offer a digital twin of the robotic platform. Via real-world experiments, we evaluate the impact of latency and packet loss on user satisfaction with our framework.**

***Index Terms*—Remote Experience Center, Teleoperation, OpenAirInterface, Digital Twin, Real-world Experiment, Robotics, Mobile Network**

## I. INTRODUCTION

Teleoperation has become increasingly vital in various fields, such as medical care [1]–[3] and industrial automation [4], [5], enabling humans to remotely control a robot for tasks ranging from hazardous environments and to sense multimodal feedback (*e.g.*, visual and haptic feedback) during the interaction. However, high-fidelity long-distance teleoperation remains challenging due to limitations imposed by the quality of communication networks between the leader (the human operator) and the follower system (the robot platform). With the advent of 5G/6G mobile networks, previously unavoidable communication network barriers (*e.g.*, latency, jitter, and limited bandwidth) can be mitigated, sparking considerable interest among teleoperation researchers eager to integrate their systems with these cutting-edge mobile networks. Similarly, communication network researchers are keen to see their technologies applied in the robotics field.

Despite this mutual interest, a significant gap still exists between the fields of robotics and communication networks. On the one hand, robotics researchers often lack expertise in advanced mobile network architectures and systems and access to communication testbeds. On the other hand, communication network researchers typically lack knowledge of teleoperation or robot control systems and do not have access to robot platforms for testing their networks in real-world applications. This disconnection hinders the seamless integration of robot teleoperation and communication networks.

To this end, we introduce the concept of a Remote Experience Center (REC) designed to connect research teams in two cities, one specializing in robotics and the other in communication networks. The REC allows to remotely share infrastructure of both teams to test and validate research in robotics or in communication networks. To practically implement and explore the REC concept, we demonstrate the REC for teleoperation between Munich and Prague, leveraging mobile networks. Specifically, we deploy a software-defined mobile network testbed in Prague and a robot platform in Munich, demonstrating our framework's capabilities through performance evaluations of two classical teleoperation tasks (*i.e.*, pick-and-place and peg-in-hole task) using the mobile network. To enhance the teleoperation experience, we integrate visual feedback from an external camera and force feedback generated through the inverse kinematics calculations of the robot arm. We conduct experiments under various mobile network conditions (varying latency and packet loss ratio). In addition to the physical robot platform and the mobile network, we provide the digital twin of the robot platform to allow researchers to focus on their respective domains without

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[*] Dong Yang and Adam Janes contributed equally to this work and are co-first authors.

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risking potential damage to real experimental equipment. The digital twin enables researchers to test new approaches and algorithms in a safe virtual environment. Once the new approaches are validated to work effectively in the digital twin, a seamless deployment on the physical robotics hardware can be done. The digital twin is validated to closely replicate the behavior of the physical devices, ensuring the reliability and consistency of our framework. Furthermore, the subjective user study indicates high usability of the digital twin and a positive user experience with the REC, demonstrating the practical effectiveness of our framework.

In the remainder of this paper, Section II discusses key developments in teleoperation systems and mobile networks. Section III presents the proposed system architecture from both teleoperation and mobile network perspectives. In Section IV, we detail the experimental setup and the description of robotics tasks deployed in the experiments. Afterward, the results based on objective and subjective metrics are discussed. Section V concludes this paper and discusses future research.

## II. RELATED WORK

In a typical bilateral teleoperation system, robot control commands from the human operator, along with visual and haptic feedback from the robot side, are transmitted through a wireless communication network [6]. Existing studies primarily focus on how to deal with communication network issues to achieve high-fidelity teleoperation experiences. One line of work employs passivity-based control schemes, such as the time domain passivity approach (TDPA) and its variants [7]–[9], or model-mediated teleoperation (MMT) [10] frameworks, which aim to maintain system stability and improve transparency in the presence of communication latency or packet loss, ensuring robust teleoperation performance under adverse communication conditions. In contrast, other studies leverage shared control schemes, where the human operator and the assistive system collaboratively execute desired tasks [5], [11]. These approaches improve safety and efficiency by allowing the system to assist the human operator during tasks, especially when network issues, such as latency or packet loss, lead to misjudgments by the human operator, resulting in potentially risky commands to the robot.

However, the aforementioned studies utilize relatively simple and basic communication networks, limiting their applicability to real-world scenarios involving complex or next-generation networks. This gap arises from the lack of integration between teleoperation and advanced mobile communication network research. Our REC is designed to facilitate the seamless collaboration between teleoperation and cutting-edge communication mobile network research by establishing a reliable, easy-to-replicate teleoperation framework standard between two cities. Our framework is also modular, enabling easy adoption even in the absence of specific background knowledge. This provides a solid foundation for interdisciplinary and multi-team collaboration of any research teams in robotics and communication systems.

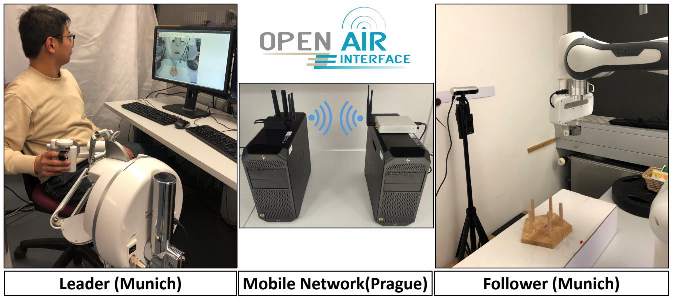

Fig. 1: Peg-in-hole task scenario using the physical robot platform in Munich and the mobile network in Prague. Our REC enables a cross-city teleoperation integrated with the setup and knowledge of two teams. The robot control commands, the visual feedback by the external camera, and the force feedback calculated on the follower side are transmitted over the mobile network with various configurations of latency and packet loss ratio.

## III. SYSTEM ARCHITECTURE

Our framework comprises the robot platform and the haptic device located in Munich, the physical software-defined mobile network in Prague, and a virtual private network (VPN) connecting these components (see Fig. 1). In the following subsections, we present individual parts in detail.

### A. Robot Platform in Munich

The teleoperation part of REC is built on the basis of a classical position-force bilateral teleoperation setup. We employ the Force Dimension® Sigma 7 haptic input/output device as the leader. A seven degrees of freedom (DoFs) Franka Emika robot arm is used as the follower. Both devices are selected because they are widely deployed and can provide high-precision control in teleoperation tasks. To control the follower robot in a compliant and stable manner, our robot controller is implemented using the Cartesian impedance control strategy [12] based on Franka Control Interface (FCI)*. The desired position of the robot end-effector $\boldsymbol{O}_{desired}$ is obtained by:

$$\boldsymbol{O}_{desired} = \boldsymbol{O}_{current} + \dot{\boldsymbol{O}}_{desired} \cdot \Delta t, \tag{1}$$

where the velocity commands of the leader device $\dot{\boldsymbol{O}}_{desired}$ are transmitted to the follower robot, $\boldsymbol{O}_{current}$ denotes the current position of the robot end-effector, and $\Delta t$ is 1 ms for the control frequency of 1 kHz on the robot side.

Then, we calculate the Cartesian task torque $\boldsymbol{\tau}_{cart}$ to drive the robot arm joints to the desired position as follows:

$$\begin{aligned} \boldsymbol{\tau}_{cart} &= \boldsymbol{J}(\boldsymbol{q})^T \boldsymbol{F}_{ee}, \\ \boldsymbol{F}_{ee} &= K\boldsymbol{e} + D\dot{\boldsymbol{e}}, \end{aligned} \tag{2}$$

where $\boldsymbol{J}(\boldsymbol{q})^T$ indicates the transpose of the robot arm's Jacobian, $\boldsymbol{F}_{ee}$ is the computed force at the end-effector, $\boldsymbol{e}$ is the error between the current position and the desired position of the robot end-effector and $K$ and $D$ represent Cartesian stiffness and damping matrix, respectively.

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*FCI documentation: https://frankaemika.github.io/docs/

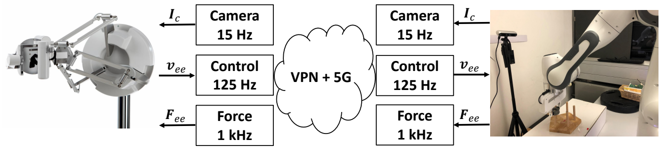

Fig. 2: Overall system with robotic input (leader) and output (follower) of REC interconnected via mobile network.

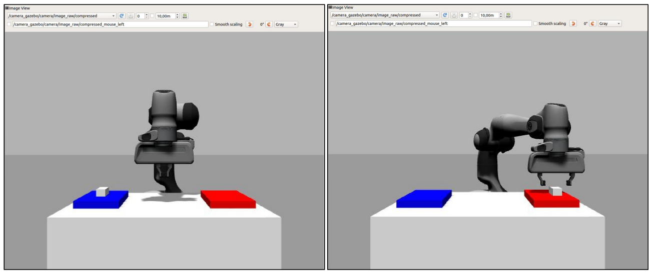
(a) (b)

Fig. 3: Camera view displayed to the human operator during the pick-and-place task using the digital twin robot platform showing (a) initial position with the block on blue tray and (b) final position, when the human operator remotely places the block on the red tray.

As depicted in Fig. 2, to enhance the operator's perception of the remote environment, we provide visual and haptic feedback in our framework. Visual feedback is acquired through the Intel® RealSense D455 camera. Since the Franka Emika robot arm is not equipped with a force-torque sensor at its end-effector, we use the control force $\boldsymbol{F}_{ee}$ in (2) as a substitute for the haptic feedback during the teleoperation. However, due to the unavoidable latency between Munich and Prague, directly rendering $\boldsymbol{F}_{ee}$ on the leader side, oscillations around the desired position can be triggered. Therefore, we scale $\boldsymbol{F}_{ee}$ and manually damp the force on the leader side to trade off the stability and accuracy of the force feedback.

Although the robot arm lacks direct measurement of real-world forces, it approximates the expected interaction forces. Such approximation is sufficient for most of the teleoperation tasks. In addition to the physical robot platform, we offer its digital version in the Gazebo simulator to enable safe, scalable and convenient experimental testing (see Fig. 3). This allows researchers to conduct experiments without the risk of damaging physical equipment and facilitates collaboration across teleoperation and communication domains without requiring direct access to the real robot arm.

### B. Interconnection of Robotic and Mobile Networks Testbeds

To build our REC framework, we use four computers connected to the same VPN. Two computers are located in Munich primarily working on the teleoperation part. The other two computers are located in Prague and are primarily involved in the mobile network part. A detailed scheme is shown in Fig. 4.

For the pick-and-place task, the digital robot platform runs on PC_TUM_SIM. The leader side (*i.e.*, the control of the haptic device) runs on the second computer in Munich (PC_TUM_CON). For the physical setup (*i.e.*, peg-in-hole task), PC_TUM_SIM controls the leader device, and PC_TUM_CON connects directly to the real robot arm to receive the control commands. Both components on the Munich side run in the ROS environment.

The first computer in Prague (PC_CTU_UE) behaves as User Equipment (UE) within the mobile network. The modem Quectel RM520N-GL is connected to PC_CTU_UE via USB and provides communication over the mobile network. The second computer in Prague (PC_CTU_gNB) behaves as gNodeB (gNB) in the mobile network. The same computer also runs 5G Core (5GC). For radio communication, Universal Software Radio Peripheral (USRP) B210 is connected to PC_CTU_gNB. The USRP with PC_CTU_gNB establishes the connection with the UE and guarantees data exchange. The setup used for the mobile network is shown in Fig. 5.

For the routing setup to utilize the mobile network, we need to encapsulate the connection between PC_TUM_CON and PC_CTU_UE and between PC_TUM_SIM and PC_CTU_gNB. The encapsulation is required due to routing rules where the default routing settings could cause communication between PC_TUM_SIM and PC_TUM_CON to not use the mobile network. To encapsulate the communication channel using the VPN connection, we apply Generic Routing Encapsulation (GRE) tunneling. Also, a GRE tunnel is established between PC_TUM_SIM and PC_CTU_UE to force the use of the mobile network. After the described setup and adjustment of ROS variables ROS_IP and ROS_MASTER_URI using IP addresses of the GRE tunnels, the two ROS environments on PC_TUM_SIM and PC_TUM_CON are interconnected using only one ROS master node.

### C. Mobile Network in Prague

The mobile network operates within the framework of the OpenAirInterface (OAI) software [13]. We employ the UHD version 4.6 for the experiments, OAI gNB software is built with tag 2025.w02. The mobile network operates at 3.5 GHz (n78) with a bandwidth of 20 MHz. We consider modulation and coding scheme 24 (modulation 64QAM and code rate 0.754 [14]), 106 resource blocks, downlink and uplink periodicity of 5 ms, downlink and uplink pattern: 6 slots for downlink and 3 slots for uplink. The 5G core network (5GC) running on PC_CTU_gNB is deployed in a docker environment to guarantee all parts of the 5GC communicate between each other correctly. The OpenAirInterface 5GC is divided into several components, see [13]. The network setting to control latency and packet loss ratio is modified mainly in the user plane function (UPF) component.

During the experiments, the positions of the UE and the gNB are kept constant. The average latency of ICMP messages, measured over 100 messages, is 64.3 ms between PC_TUM_SIM and PC_TUM_CON using the 5G network and VPN. The VPN connection contributes 35.9 ms of la-

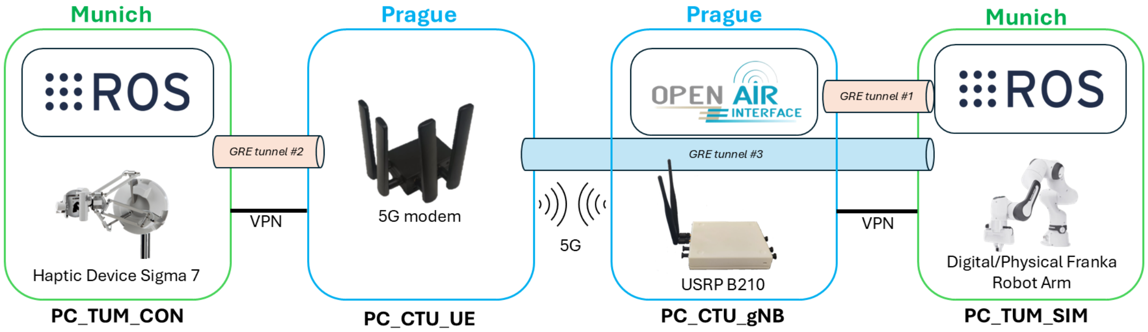

Fig. 4: Overview of REC for telerobotics experiment via mobile network.

Fig. 5: Mobile network setup in Prague: PC_CTU_UE (2) communicates via mobile network with PC_CTU_gNB (4) using modem (1) and USRP B210 (3).

tency, accounting for 55.8% of the total latency between PC_TUM_SIM and PC_TUM_CON.

## IV. EXPERIMENTS

### A. *Task Description*

We use two classical teleoperation tasks, *Pick-and-place* and *Peg-in-hole*, to evaluate our framework using physical and digital robot setups under different network conditions. In both tasks, haptic feedback is simulated by the calculated control force, as described above. The initial pose of the robot arm is fixed and the same for all experiments.

*1) Pick-and-place Task:* As shown in Fig. 3, this task is performed in the Gazebo simulator using the digital twin version of the robot platform. The human operator is required to control the robot arm to pick up the designated object (*i.e.*, the white block) from the blue tray and then place it on the red tray. A fixed camera positioned in front of the robot arm provides visual feedback to the operator.

*2) Peg-in-hole Task:* In this task, the objective is to insert the gray block into the vertical wooden rod by aligning the hole in the block with the rod (see Fig. 1). It is carried out using the physical robot platform with a camera mounted in front of the robot arm to deliver visual feedback.

### B. *Experimental Scenarios*

The experiment is designed to comprehensively evaluate the feasibility of our REC framework under varying mobile network conditions and both physical and digital robot setups. The aim is to assess the performance of cross-city teleoperation tasks using REC framework objectively and subjectively, ensuring its robustness and usability in real-world scenarios. To do that, we involve 10 participants in our experiments. Before each teleoperation task, the participant undergoes a training session to gain basic skills and understanding to perform the task. Afterward, each participant is required to conduct the two aforementioned teleoperation tasks, repeating each task five times. Out of the five trials, one represents the original cross-city teleoperation setup, while the other four include additional network impairments: additional 40 ms and 100 ms latency, 10% and 20% packet loss ratio, respectively. Latency and packet loss are selected because both have a significant effect on the execution of the teleoperation tasks. The parameter setting is done using the Linux kernel utility Traffic control. We use this kernel utility to affect the uplink. For this reason, we apply half the value on both the UE and the gNB side to affect the control, feedback commands, and camera messages equally.

To obtain insights into the subjective experiences of participants while using our framework, after each trial of the task, each participant is instructed to complete a questionnaire to assess the workload using a 1-7 Likert scale using the NASA Task Load Index (NASA-TLX) [15], which is a widely-used tool to measure various dimensions of task load. This study has been approved by the ethics committee of Technical University of Munich under the number 2023-401-S-NP. We define the following metrics for the assessment:

*1) Objective Metrics:* The following two objective metrics are evaluated:

- *Success Rate*: Measured as the percentage of successful task completions, *i.e.*, placing the white block on the red tray in the pick-and-place task, or inserting the gray block into the wooden rod in the peg-in-hole task. The release of the robot gripper indicates the end of the task.
- *Task Completion Time*: Measured as the time duration from the robotic arm's starting position to the release of the gripper. The starting position is consistently reset to the same configuration before each trial.

*2) Subjective Metrics:* To evaluate the user experience, we collect the users' subjective feedback from questionnaires by rating the six indexes:

- *Mental demand* – how much mental and perceptual activity is required;

TABLE I: Average results of experiments by 10 participants

| Task | Configuration | Mental Demand ↓ | Physical Demand ↓ | Temporal Demand ↓ | Performance ↑ | Effort ↓ | Frustration Level ↓ | Success Rate (%) ↑ | Completion Time (s) ↓ |
|---|---|---|---|---|---|---|---|---|---|
| Pick-and-place | Original | **2.2** | **2.0** | **2.0** | **6.0** | **2.2** | **1.9** | **100** | **81.13** |
| | +40 ms Latency | 3.5 | 3.0 | 3.0 | 5.5 | 3.1 | 2.7 | 90 | 93.48 |
| | +100 ms Latency | 4.5 | 4.0 | 4.0 | 4.3 | 4.1 | 4.2 | 90 | 110.11 |
| | +10% Packet Loss | 3.6 | 3.1 | 3.8 | 4.3 | 3.5 | 3.1 | 80 | 95.60 |
| | +20% Packet Loss | 4.9 | 4.1 | 4.8 | 3.0 | 4.8 | 4.8 | 60 | 126.76 |
| Peg-in-hole | Original | **2.1** | **1.9** | **1.8** | **6.3** | **2.2** | **1.9** | **90** | **56.52** |
| | +40 ms Latency | 3.0 | 3.0 | 2.5 | 4.7 | 3.7 | 2.7 | 60 | 62.38 |
| | +100 ms Latency | 5.1 | 4.7 | 4.6 | 3.4 | 4.8 | 4.9 | 60 | 92.02 |
| | +10% Packet Loss | 2.9 | 2.8 | 2.5 | 5.0 | 3.4 | 2.3 | 60 | 56.68 |
| | +20% Packet Loss | 4.0 | 3.9 | 3.1 | 4.2 | 4.1 | 3.4 | 70 | 70.62 |

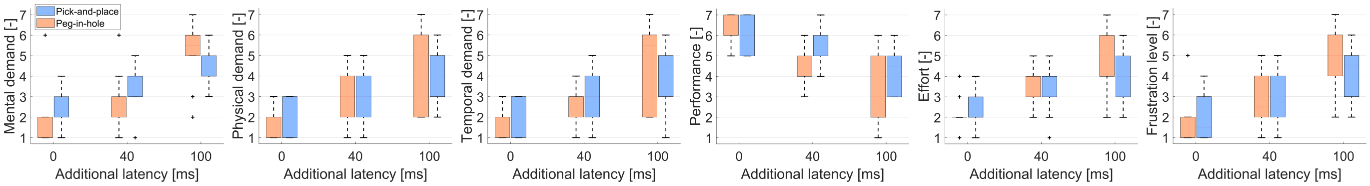

Fig. 6: Comparison of subjective results depending on additional latency. Blocks represent the spread between the first (Q1) and third quartile (Q3). Whiskers represent the range of data within 1.5 times the interquartile range (IQR) from the first and third quartiles. Outliers are data points that fall outside this range and are plotted individually.

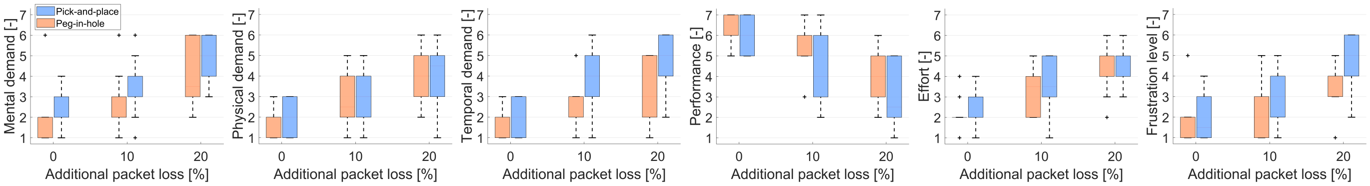

Fig. 7: Comparison of subjective results depending on additional packet loss. Blocks represent the spread between the first (Q1) and third quartile (Q3). Whiskers represent the range of data within 1.5 times the interquartile range (IQR) from the first and third quartiles. Outliers are data points that fall outside this range and are plotted individually.

- *Physical demand* – how much physical activity is required;
- *Temporal demand* – how much time pressure the participant feels due to the rate or pace at which the task occurs;
- *Performance* – how successful or satisfied does the participant think is in accomplishing the goals of the task;
- *Effort* – how hard the participant has to work mentally and physically to accomplish the participant's level of performance;
- *Frustration level* – how insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent does the participant feel during the task.

These indexes are reported as numbers ranging from 1 to 7, where 1 is the lowest and 7 is the highest. By these metrics, we aim to comprehensively evaluate the cognitive and physical burden imposed by REC under different circumstances.

### C. Results

*1) Objective Experimental Results:* As depicted in Table. I, the objective results align with our expectations: The original network configuration yields the highest success rate in all scenarios, while the introduction of additional latency and packet loss results in a lower success rate. This demonstrates the negative impact of the worsened mobile network parameters on the performance of teleoperation tasks. Task completion time follows a similar trend, increasing latency and packet loss results in the prolongation of the task duration. Furthermore, the performance of the digital robot platform (*i.e.*, in the pick-and-place task) closely mirrors that of the physical robot platform (*i.e.*, in the peg-in-hole task), highlighting the precision and reliability of the digital twin.

*2) Subjective Experimental Results:* The subjective results indicate that the original mobile network configuration provides the highest user experience for the human operator. Thus, the tasks are completed more efficiently with a higher success rate than using the other network configurations. However, participants report a significant increase in their workload required to complete the same tasks after the application of large additional latency or packet loss (*i.e.*, 100 ms latency and 20% packet loss ratio). This is because of the notable delay or lack of responsiveness in visual feedback, which heavily impacts the human operators' perception of the robot arm position and, thus, can lead to unnecessary or incorrect movement. Moreover, since our framework simulates force feedback using the calculated control force, inaccurate force feedback caused by added latency or packet loss further decreases the user experience. Fig. 6 and Fig. 7 show the detailed distribution of subjective results in both tasks.

### *D. Discussion*

It is worth noting that some subjects who have no experience with teleoperation report that the additional 40 ms latency and 10% packet loss ratio are not particularly noticeable, because these users prefer to control the robot arm more slowly to complete the task. Most subjects think visual feedback is the most important way to perceive the task scenarios. The subjects also report that the perceived force feedback is not apparent, since they experience tiny force during movements in free space and only a relative "soft" force upon obvious contact with the table. This behavior is caused by the use of force scaling and damping strategy for ensuring stable interaction during teleoperation.

From the network perspective, the results show that connection quality is critical for teleoperation tasks, as all metric ratings get worse when latency or packet loss ratio increases compared to the original network status. Nevertheless, due to the distributed system, almost the same latency corresponding to the wireless connection in the Prague testbed is already introduced by using the VPN. In addition, both research teams from Munich and Prague find the proposed framework intuitive and effective, enabling seamless collaboration despite their different expertise. This confirms its success in bridging disciplinary gaps and fostering interdisciplinary research on teleoperation and mobile communication.

## V. CONCLUSION

This paper presents the concept of the Remote Experience Center (REC) and its practical implementation for teleoperation that bridges the gap between robotics and communication networks research. By integrating physical and digital robot platforms in Munich with the real mobile network in Prague, the framework provides a reliable and replicable setup for cross-disciplinary collaboration. We invited 10 individuals to perform 100 experiments in total to validate our framework. The results align with the expectation that an additional latency or packet loss negatively affects task performance and user experience. The behavior of the digital robot platform closely replicates that of the physical system, enabling flexible and safe experimental research while reducing the cost of real-time coordination between geographically dispersed teams. Despite its limitations, including imperfect force feedback and inherent latency introduced by the VPN connection between the two sites, the proposed framework provides a scalable foundation for future research into long-distance teleoperation systems. It paves the way for more robust, efficient, and accessible solutions in next-generation mobile network environments.

One key avenue of future work is the integration of the more advanced simulator (*e.g.*, NVIDIA Omniverse) and the 6G research testbeds into our framework, enhancing our framework's performance on more complex teleoperation tasks.

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