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Towards the New Generation of Smart Home-Care with Cloud-Based Internet of Humans and Robotic Things

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Abstract— **The burgeoning demand for home-care services, driven by a rapidly aging global population, necessitates innovative solutions to alleviate the burden on caregivers and enhance care quality. This paper introduces the development of an Internet of Human and Robotic Things (IoHRT) framework, which synergizes cloud computing and the Internet of Robotic Things (IoRT) with human-robot collaborative control mechanisms for home-care applications. The IoHRT framework is designed to enable the seamless integration of customizable robotic platforms with modular, scalable, and compatible features, thereby creating a dynamic and adaptable home-care ecosystem. By leveraging the scalability and computational power of cloud computing, the framework facilitates real-time data analysis and remote monitoring, thus enhancing the efficiency and effectiveness of home-care. We present an in-depth analysis of the key characteristics of IoHRT, supported by evidence embedded in our design, and conduct user studies to evaluate the framework from users' perspectives. We demonstrate the performance and utility of our proposed framework for the future of home-care applications.**

I. INTRODUCTION

The Internet of Robotic Things (IoRT) [1], a concept merging the advantages of the Internet of Things (IoT) and robotics [2], has found applications in many domains, including retail [3], agriculture [4], and clinical systems [5]. This technology allows multiple robots to share data efficiently and collaborate on tasks, leveraging the support of the IoT infrastructure [6].

In this paper, we extend the concept of IoRT by incorporating a human-robot shared control mechanism into traditional IoRT frameworks. This integration combines human cognitive abilities with robotic precision for task execution. With this in mind, we introduce a comprehensive framework, called the Internet of Humans and Robotic Things (IoHRT). While existing IoRT frameworks focus on seamless connections between IoT and robots, IoHRT aims to unify these diverse components into an ecosystem that enhances real-time data analysis, remote monitoring, and HRI, specifically tailored for home-care applications. This specialized framework incorporates modular, scalable, and compatible features, ensuring a more effective and adaptable solution for integrating robotic assistance with human-in-the-loop control.

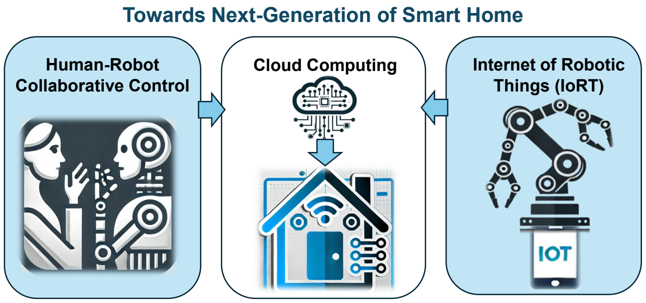

Fig. 1. Illustration of the concept of IoHRT for smart-home applications.

To support the development of IoHRT, cloud infrastructure is vital. The recent advancement of cloud infrastructures has led to the emergence of cloud robotics paradigms. Cloud robotics can be seen as a fusion of robotics, big data, and cloud computing techniques [7], laying the foundations for developing high-performance, multi-robot systems through network connections [8]. A cloud server can centralize all resources, including environmental information gathered by sensors, actuator states, and perception data obtained via robots [9], facilitating efficient data processing and communication among various robotic platforms. With the available data, cloud computing can accelerate AI model training and transform collected data into valuable robot intelligence [10]. Consequently, we implement the IoHRT architecture on a cloud server with a centralized hierarchy for managing resources and controlling multiple robotic systems. The concept of IoHRT is illustrated in Fig. 1.

The **main contributions** of this paper include:

- The development of the IoHRT concept, and the creation of a unified framework serving as a fundamental architecture for home-care applications.
- The integration of a human-robot shared control mechanism to facilitate seamless cooperation between humans and robots in home-care applications.
- The deployment of the proposed framework on a cloud service with a modular control panel and a system designed for easy integration of new robotic platforms, which benefits the robotic community.
- The evaluation of the framework's effectiveness through stress tests, latency tests, and user studies.

The structure of this paper is organized as follows. Section II introduces related work in the field. Subsequently, the framework and case studies are presented in Section III. Section IV presents detailed user studies that demonstrate the functions and evaluate the effectiveness of the proposed framework. Finally, conclusions are drawn in Section V.

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II. RELATED WORK

Platforms such as Home Assistant (HA) and Open Home Automation Bus (OpenHAB) have been developed to enable the seamless integration of numerous IoT devices from diverse manufacturers [11]. Both of these platforms are open source and free of charge. However, these platforms, known as traditional IoT frameworks, they have not demonstrated the integration of multiple robotic systems as an IoRT architecture [12].

For home-centric healthcare applications, IoRT has been identified as a promising future direction, particularly in supporting independent living for elderly people [13]. The ABB Yumi robot has been employed by harnessing IoT-aided teleoperation and a wearable motion tracking system to generate control commands for robot teleoperations [14]. Additionally, a nursing robot using IoRT has been developed to alleviate behavioral disturbances in Persons with Dementia (PWD). Wearable devices on PWDs, combined with environmental sensors, can notify caregivers, while the Zora robot can be instructed to perform customized interventional tasks [15].

During the fight against the Coronavirus, an innovative IoRT approach was implemented to ease the strain on medical and nursing staff [16]. These robots gathered medical data and uploaded it to the cloud for doctor interpretation. Moreover, they served as a bridge between onsite elements and the cloud in hospitals, contributing to patient data storage and real-time transmission [17]. This mechanism enhanced the ability of medical staff to oversee quarantine compliance and monitor patients' health, aiming to reduce human contact.

Furthermore, cloud computing enhances the potential of robots by providing them with unparalleled cognitive capabilities through deep learning training processes [18]. Notably, the C2TAM framework [19] is tailored for Simultaneous Localization and Mapping (SLAM) within robotics. With the support of cloud computing platforms, robots can share data seamlessly and access information for their tasks without navigating complex communication protocols. While cloud robotics shows potential for assisted living, a significant gap remains: the integration of human-robot shared control in home-care cloud robotic systems and the development of a modular, user-friendly, and compatible framework for the easy integration of various HRI devices remains largely unexplored.

III. METHODOLOGY AND CASE STUDY

A. Architecture

Building on these design principles, we develop the IoHRT framework, which features an architecture that supports extensive interfaces for seamless transitions between various software and hardware components, without necessitating modifications to the core software. This flexibility enables the execution of a wide range of tasks across multiple robotic platforms, as illustrated in Fig. 2 (a). The proposed framework comprises three distinct layers: the Physical Layer, the Cloud Layer, and the Application Layer, each described in detail below.

*1) **Physical Layer:*** The Physical Layer incorporates assistive or service robots tailored for home-care scenarios, sensors dedicated to robotic perception or environment monitoring, and actuators directing autonomous devices. Microcontrollers are used to capture real-time sensor data and send them to the cloud for further analysis. A local server facilitates communication between the cloud service and the local workstations that control multiple robotic platforms. This server also coordinates incoming requests from the cloud. A TCP socket, ensuring smooth integration between robot-specific APIs and the cloud platform, is employed as the communication protocol. For Robot Operating System (ROS)-based robotic systems, the integration with the IoHRT framework can be streamlined using a ROS and TCP/IP connection package [1]. This package plays an important role in bridging the communication between ROS and IoHRT.

*2) **Cloud Layer:*** The cloud layer is built on Amazon Web Services (AWS), which provides the essential infrastructure for data storage, transmission, processing, and analytics through high-performance cloud servers hosting applications and databases. Data storage is managed using MongoDB, a renowned NoSQL database known for its resilience, scalability, and geographically distributed functions. Communication with the physical layer is streamlined through a TCP socket that enables data exchange using JSON-serialized messages among robots, sensors, and servers. The cloud server handles data processing in two primary modes: real-time stream processing and subsequent analysis. Real-time processing identifies anomalies and delegates inspection tasks to robots, while post-processing involves detailed analysis and predictive modeling. Advanced computational techniques, such as machine learning-based data analysis and autonomous robot control, can be deployed on the cloud server to enhance functionality.

*3) **Application Layer:*** The application layer involves user interfaces and protocols for managing, monitoring, and controlling robotic systems. It features a web interface built with Django, a high-level Python web framework[2]. Initially, users can launch the Django server and access the framework through a specified URL in their browsers. Robots can be registered on the platform by providing essential details and establishing a connection with the framework's TCP server. Within the application layer, remote end-users can view data gathered by environment or robot-affixed sensors. For robotic platform integration or management, users are advised to log in using an admin account. After account registration and permission, these authorized users can remotely control robots or actuators via a web browser. User data is securely housed within a Django-constructed database, with authentication facilitated by Django's system during login.

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[1] `https://github.com/abhinavjain241/comm_tcp`

[2] https://developer.mozilla.org/en-US/docs/Learn/Server-side/Django

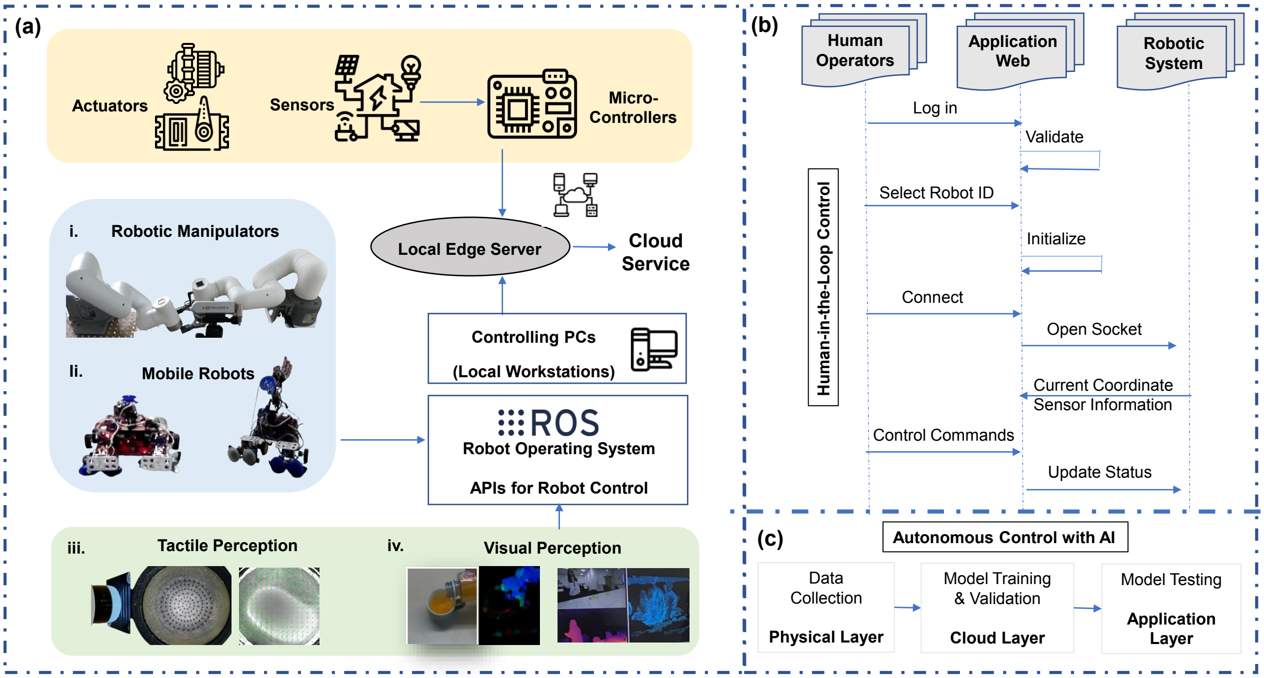


Fig. 2. Techical implementation details. (a) Illustration of the physical layer. i: mobile manipulators; ii: mobile robots, image adapted from [20]; iii: robotic tactile perception, image adapted from [21], [22]; iv: robotic visual perception, image adapted from [23]. (b) Sketch of the human-in-the-loop control scheme; (c) Sketch of the autonomous control scheme.

B. Human-Robot Shared Control

The construction of the IoHRT framework for home-care applications necessitates the seamless integration of human proficiency and the efficiency of robotic systems. To this end, we integrate a human-robot shared control mechanism into the IoHRT framework. This mechanism could potentially enhance overall teleoperation efficiency, while safety can be ensured in the meantime. For example, the robot can autonomously execute tasks, while human-in-the-loop control can be activated via giving control commands using HRI interfaces.

To reach this target, human operators can generate control commands to specify the target object for the robot to manipulate and could alter the trajectory for object transportation during challenging manipulation tasks to improve efficiency and success rates [24]. The control relationship between the commands generated by human operators and the robot's movements for 'human-robot shared control' can be calculated by (1). Assume that $\boldsymbol{V_r(t)}$ is the incremental value for control determined by the robot, $\boldsymbol{V_h(t)}$ is the control commands generated by human operators, obtained through user interfaces. $\boldsymbol{P_s(t)}$ can be calculated by (1) for robot end effector motion control.

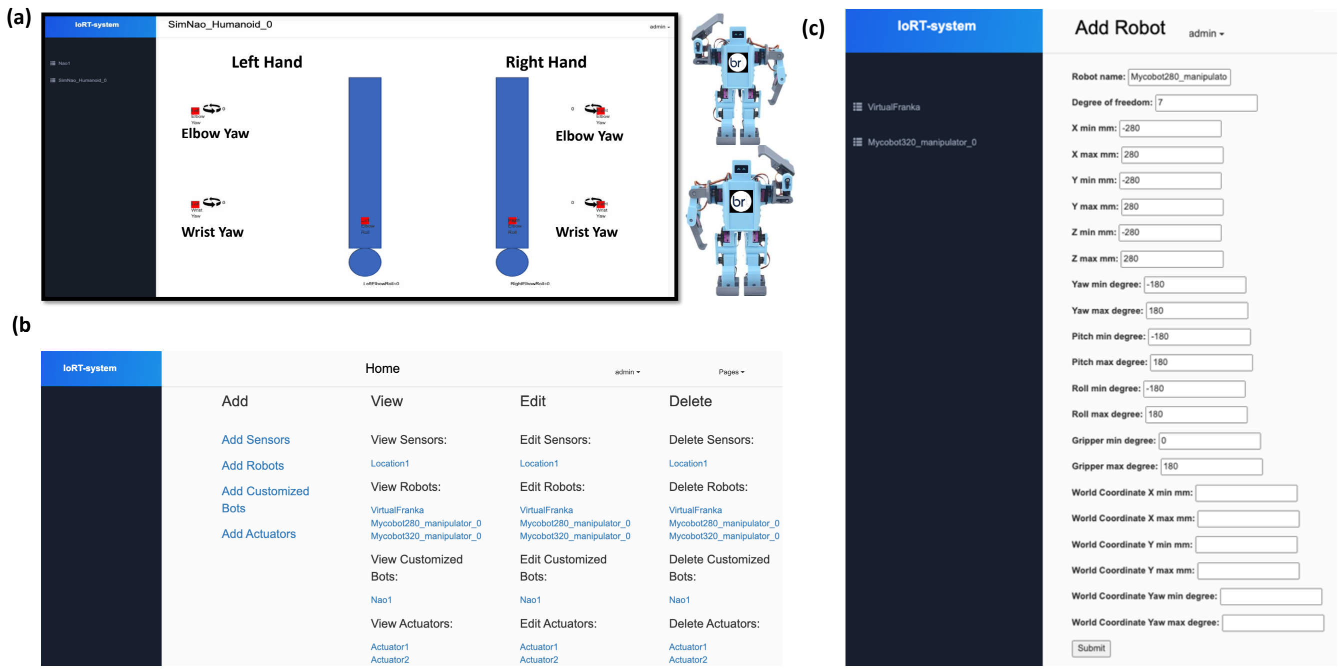
$$\boldsymbol{P_s(t)} = [(1-m)\gamma \boldsymbol{V_h(t)} + m\boldsymbol{V_r(t)}]\Delta t + \boldsymbol{P_s(t-1)} \quad (1)$$

$m{\in}[0,1]$ is a weight parameter determined by the relative importance of control commands generated by humans and robots. γ represents the motion scaling ratio [25], which can be modified based on user preference. The signal transmission among human operators and robots through an application web is illustrated in Fig. 2 (b). $m=0$ is used for teleoperation, $m{\in}(0,1)$ is used for fusing human's and robot's generated commands in an appropriate manner [26]–[28]. The user can select different autonomy levels by tuning m. $m=1$ is used for fully autonomous task execution. The training process for the intelligent robot for autonomous task execution is illustrated in Fig. 2 (c). The ongoing and future activities on IoHRT will incorporate deep imitation learning or deep reinforcement learning algorithms to train intelligent robots for autonomous task execution [29]–[31].

C. Characteristics of IoHRT

Security: The framework features a security control module utilizing password-based authentication. The users' operation data will be stored in their accounts to ensure security. This can also help reduce mutual influence among users in the meantime. General users can access the webpage and view environmental sensing data, and robot perception data, while only authorized users can access the robot control dashboard and remotely control robots.

Evidence: Authorized users can control the robots or actuators through a web browser by registering an account through the website. User information is stored in a built-in database (MongoDB) in Django and authenticated by the Django authentication system during login. Each user can be assigned different types of permissions. Users with read-only access could only view the web page of 'multi sensors' for environment monitoring. Individuals with robot control access can operate one or more specific robots. If abnormal states of the environment are discovered, the system can automatically alert security professionals to deal with emergencies by sending messages or emails.



Add Robot

Robot name: Mycobot280_manipulato
Degree of freedom: 7
X min mm: -280
X max mm: 280
Y min mm: -280
Y max mm: 280
Z min mm: -280
Z max mm: 280
Yaw min degree: -180
Yaw max degree: 180
Pitch min degree: -180
Pitch max degree: 180
Roll min degree: -180
Roll max degree: 180
Gripper min degree: 0
Gripper max degree: 180
World Coordinate X min mm:
World Coordinate X max mm:
World Coordinate Y min mm:
World Coordinate Y max mm:
World Coordinate Yaw min degree:
World Coordinate Yaw max degree:

Fig. 3. Illustration of the user control panel on the web page and the experimental setup of a case study. (a) Interaction with a humanoid using a customizable control panel on the web service provided by the IoHRT framework. (b) Illustrate the user interface for adding, viewing, editing, and deleting robots. (c) Illustrate the process of adding specifications for a new robotic system.

Scalability: The IoHRT framework implements a device management system that supports device registration, configuration, and monitoring. Many users can operate multiple robotic platforms simultaneously without mutual interference. Additionally, the IoHRT framework supports customizable dashboards that can adapt to the growing number of devices, services, and user roles within the system.

Evidence: The web application is deployed using an Elastic Load Balancer and an Auto-Scaling Group [32]. This setup ensures that traffic is directed to healthy and less burdened instances, and instances are launched or terminated as needed based on the number of requests. Detailed latency and stress test results can be found in Section IV-B.

Compatibility: A key design consideration for the IoHRT framework is its compatibility with a wide array of robotic platforms, actuators, and sensors. To facilitate this, data structures used for information exchange conform to predefined protocols. The framework has been designed to be lightweight and executable on various operating systems. Additionally, an upgrade pathway is provided for researchers with developer access.

Evidence: The IoHRT framework streamlines the way users interact with complex robotic systems, including humanoid robots, by offering intuitive controls. A prime example is the ease of controlling a specially designed humanoid robot, known as 'SimNao,' through a web-based control panel provided by the IoHRT framework (see Fig. 3 (a)). The framework effectively combines a wide array of HRI interfaces — including joystick controllers [33], haptic controllers [34], handheld controllers [35], and wearable motion-capture devices [36], with various robotic platforms. These platforms range from commercial and custom-built robotic arms to mobile robots, mobile manipulators, and humanoid robots, facilitating seamless communication between humans and robots.

Modularity: The modular design of the architecture reduces system integration efforts when adapting the system for specific tasks. Different combinations of interaction interfaces, mapping strategies, and robotic platforms can be selected for various applications without the need to redesign the teleoperation system. When a new device is added, its information is automatically saved as a new collection in MongoDB, where all messages sent and received by the device are stored.

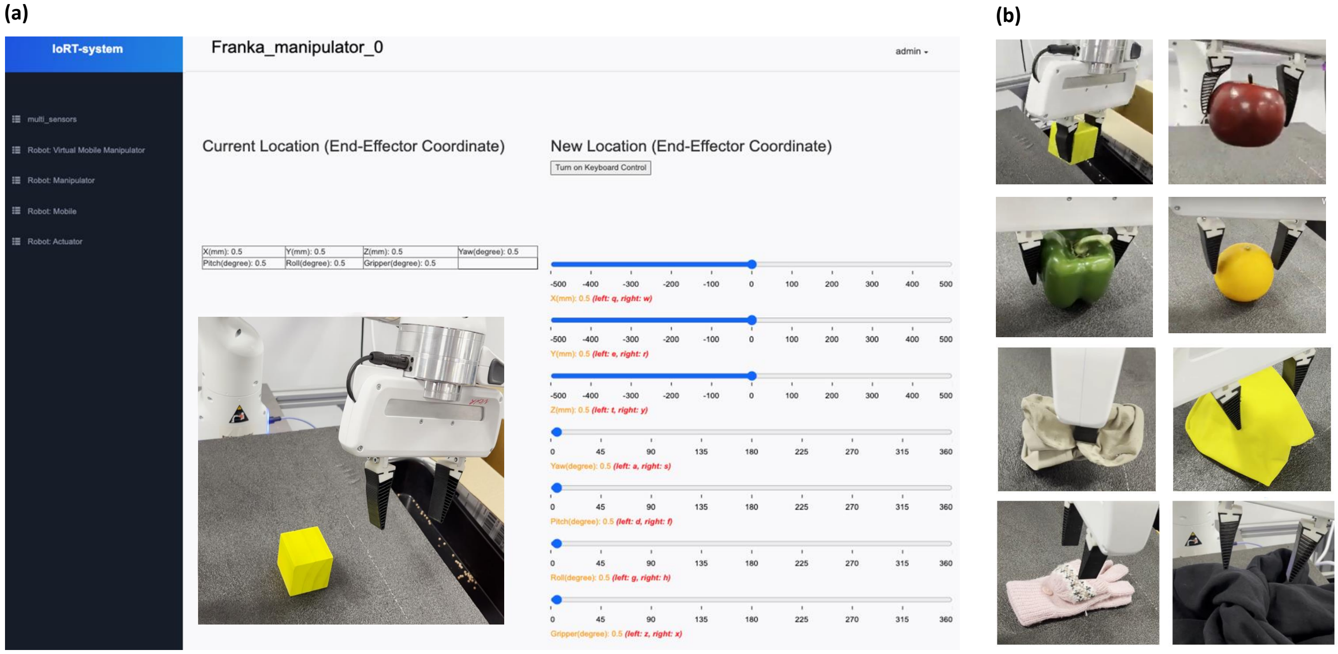
Evidence: The proposed framework has an easy-to-use control panel, which can enable users to add, delete, view, and manage various types of robotic platforms, as shown in Fig. 3 (a). Users can define the degree of freedom(DoF) and the joints' limits of the newly added robot. Fig. 3 (b) depicts the creation of a Mycobot280 robot arm (Elephant Robotics) with ID $Mycobot280\_manipulator\_0$, which has six DoF for end-effector pose control, along with an additional DoF for controlling the gripper angle. The edit webpage function enables users to modify these parameters easily.

D. Case Study: Pick-and-Place Task

This case study employs a Franka Emika Panda robotic arm, equipped with a soft gripper, to execute pick-and-place tasks. A user control interface, called Geomagic Touch (3D System), was used as a haptic controller to adjust the robots' positioning and movements [24]. The cloud server receives robot control commands via a TCP socket. The robotic arm

TABLE I. Experiment Results for case study (with and without human-robot shared control mechanism).

Without	**Cube**	**Apple**	**Chilli**	**Orange**	**Pantyhose**	**Yellow Glove**	**Pink Glove**	**Jacket**	**Mean**
Average Time	14s	18s	18s	22s	20s	17s	21s	35s	20.6s
Success Rate	100%	80%	80%	60%	100%	80%	100%	20%	77.5%
With	**Cube**	**Apple**	**Chilli**	**Orange**	**Pantyhose**	**Yellow Glove**	**Pink Glove**	**Jacket**	**Mean**
Average Time	24s	28s	32s	28	40s	44s	52s	72s	40.0s
Success Rate	100%	100%	100%	60%	100%	100%	100%	80%	92.5%



X(mm): 0.5 | Y(mm): 0.5 | Z(mm): 0.5 | Yaw(degree): 0.5
Pitch(degree): 0.5 | Roll(degree): 0.5 | Gripper(degree): 0.5

X(mm): 0.5 *(left: q, right: w)*
Y(mm): 0.5 *(left: e, right: r)*
Z(mm): 0.5 *(left: t, right: y)*
Yaw(degree): 0.5 *(left: a, right: s)*
Pitch(degree): 0.5 *(left: d, right: f)*
Roll(degree): 0.5 *(left: g, right: h)*
Gripper(degree): 0.5 *(left: z, right: x)*

Fig. 4. Overview of the experiment design of the case study for quantitative analysis based on a pick-and-place task. (a) Visualization of the user control interface. (b) The objects used for the pick-and-place task, which include a yellow cube, a red apple, a green chili, a pantyhose, a protective yellow glove, a fingerless pink glove, and a black jacket.

is then able to navigate toward the target objects, control the gripper to secure the objects from the table, and relocate them to the designated areas, i.e. an empty box.

In this study, we empirically validate the effectiveness and resilience of the proposed framework by comparing the time taken to complete the tasks and the success rate of task completion, both with and without the implementation of the human-robot shared control mechanism. To ensure a broad range of operations, eight distinct types of objects were used in the experiment, including a yellow cube, a red apple, a green chili, pantyhose, a yellow glove, a fingerless pink glove, and a black jacket (see Fig. 4). The collected experimental data are summarized in Table I.

In the absence of the human-robot shared control, the robot was expected to autonomously complete the task following a human demonstration. The results indicated a reduction in the success rate, particularly with the black jacket (at 20%). Grasping the orange also proved difficult due to its larger surface curvature compared to the other objects. As such, humans should be involved in the control loop to improve success rates. The incorporation of human-robot shared control significantly improves the average success rate (from 77.5% to 92.5%). However, this comes with an increase in the average task completion time (from 20.6s to 40.0s). To conclude, for tasks that do not have a high requirement of safety consideration, autonomous control mode can be employed by setting the task requirements. However, when handling delicate objects, the role of the human-robot shared control mechanism becomes crucial. Other case studies can be found on our project website.

IV. USER STUDIES AND RESULTS ANALYSIS

To initially validate the user experience when interacting with the system, we performed a pilot study with human users. The user studies were conducted with ethical approval obtained from the University of Bristol Ethics Committee (ref No. 15668). All participants fully and freely consented to their participation in the study. They all read the Participant Information Sheet (PIS) and signed the consent form.

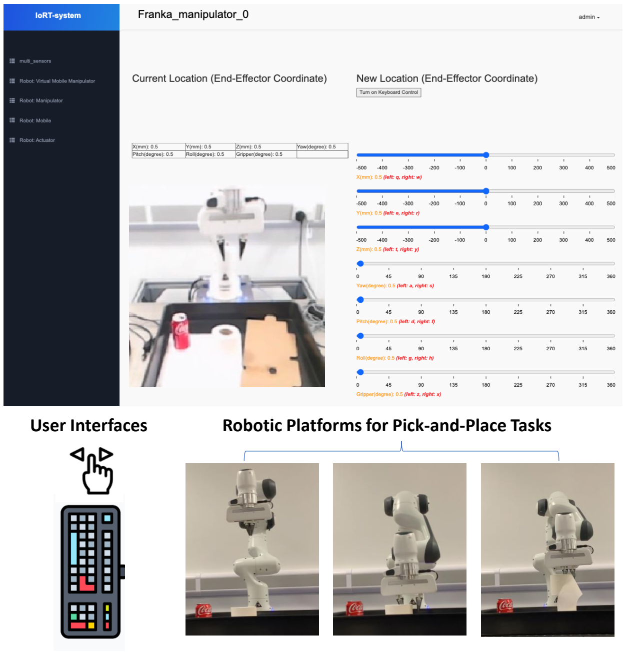
A. User Studies

1) Participants: We recruited eight participants, comprising 4 females and 4 males (aged 26-36), to evaluate, test, and provide feedback on the features of our proposed system. The participants were sourced through our professional networks. They had research backgrounds or knowledge in areas like robotic software or hardware engineering and application-based robotics. These participants are unique individuals who bring a diverse range of expertise to the user studies.

2) Experiment Design: We used a seven-joint Franka Emika Panda arm equipped with a soft gripper for the user study, as illustrated in Fig. 5. The controlling PC, running a real-time kernel in Ubuntu 20, was connected to the robot arm via Ethernet and received control commands from the cloud server through a TCP socket. The participants were required to estimate the workload of deploying the IoHRT framework for home-care applications. Participants were asked to complete a questionnaire consisting of two questions with scores ranging from 1 to 5, and an open-ended question. Higher scores indicated greater satisfaction with the system.

The questions are listed below:

- Q1: To what extent do you think the IoHRT framework is easy-to-use?
- Q2: How useful is the IoHRT framework for system integration in home-care applications?
- Q3: Why do you feel IoHRT is useful and what are the limitations of the current IoHRT framework? (open question)



X(mm): 0.5 | Y(mm): 0.5 | Z(mm): 0.5 | Yaw(degree): 0.5
Pitch(degree): 0.5 | Roll(degree): 0.5 | Gripper(degree): 0.5

X(mm): 0.5 (left: q, right: w)
Y(mm): 0.5 (left: e, right: r)
Z(mm): 0.5 (left: t, right: y)
Yaw(degree): 0.5 (left: a, right: s)
Pitch(degree): 0.5 (left: d, right: f)
Roll(degree): 0.5 (left: g, right: h)
Gripper(degree): 0.5 (left: z, right: x)

Fig. 5. Overview of the experimental setup for performing the pick-and-place task using a 7-DoF robot.

3) Results Analysis: The results of the questionnaire are summarized in Fig. 6 (a).

All participants agreed that the IoHRT is user-friendly (scored higher than 4), including 12.5% who strongly agreed (scored 5). With the support of the framework, they were able to easily interact with the robot for specific tasks. The participants commented that the system was intuitive to use, as they could easily register an account, access the system, and control any type of robot as desired. They could select robots using the GUI on the web page and control the pose of the robots. During each test, they received feedback with a negligible time delay when they generated control commands to actuate the robots. When applying the control framework to another physical robot, users only needed to switch the robot ID to reproduce the results without changing any codes. 87.5% of the participants felt that the IoHRT was helpful (scored higher than 4) for home-care applications, including 37.5% of the participants who commented that the proposed system was extremely helpful (scored 5). The users commented that the modular design decoupled all functions and modules of a teleoperation system, enabling researchers to select different interaction interfaces, mapping strategies, and robotic platforms based on their preferences. This reduces the workload for system integration when adapting to new tasks with specific control system requirements. The inherent modularity of our system allows for seamless integration and enhances the overall flexibility of the system.

The preliminary studies presented here serve to illustrate the framework's potential. Future work will involve extensive user studies with larger and more diverse participant groups, employing rigorous statistical analyses to assess the framework's effectiveness and usability comprehensively.

B. Latency Test and Stress Test

We tested the latency caused by data transmission between the server and the client for the end-user. The server is located in Virginia, US, while the client is located in Bristol, UK. The network latency was about 33.7ms, based on the average value obtained after 100 tests. The maximum latency observed during the tests was 72ms. The results are shown in Fig. 6 (b).

The stress test performed on the web service involved simulating a load of 10,000 clients per minute. Two scenarios were tested and compared. The first scenario used a single server, while the second scenario utilized an Elastic Load Balancer (ELB) and an Auto-Scaling Group (ASG) [32]. In the first scenario (Fig. 6), where a single server was used, the average response time was 69ms. However, in the second scenario (Fig. 6), where an ELB and an ASG were employed, the average response time significantly reduced to only 7ms. This indicates that the ELB effectively distributed incoming requests among multiple servers in the ASG, resulting in faster response times for each client. The use of an ASG allows the web application to dynamically adjust its server capacity based on the current load, ensuring that there are enough server resources available to handle incoming traffic efficiently. As a result, the web application can effectively handle larger workloads without sacrificing performance.

V. CONCLUSIONS AND FUTURE WORK

In this paper, we introduce a unified IoHRT framework, which integrates HRI into traditional IoRT frameworks with cloud computing. This proposed framework facilitates robots in sharing and disseminating information, accessing and sharing resources efficiently, and enabling human and multi-robot cooperative control. The integration of robotic systems in home settings aims to alleviate the care burden on healthcare professionals and family members, reduce feelings of isolation among care recipients, and improve overall care outcomes. User studies were conducted to evaluate

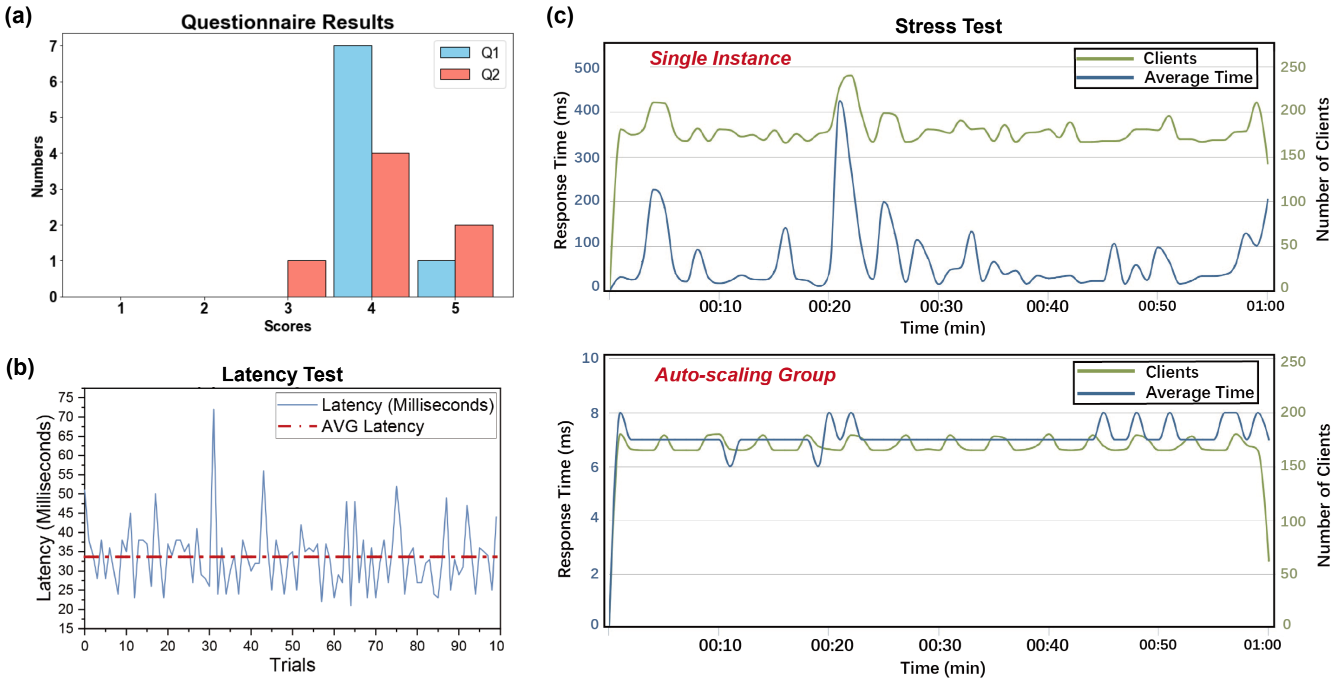


Fig. 6. Experimental results. (a) Results of the questionnaire were acquired via expert interviews. (b) Results of 100 latency test. (c) Comparison between stress tests with 10,000 clients over a single instance and using Auto-Scaling Group.

the framework's usability and satisfactory performance from users' perspectives.

In the future, we will integrate an adaptive cognitive module into the proposed framework for intelligent robots to automatically detect changes in users' habits and intentions, which can lead to dynamic role adjustment between human operators and intelligent robots. Additionally, deep imitation learning or reinforcement learning will be incorporated into the IoHRT framework to enhance intelligent robots for home-care applications. The further upgraded framework is expected to be resilient and fault-tolerant, with redundancies and backup mechanisms to ensure the continuity of care in the event of system failures or unexpected issues. While the IoHRT framework includes password-based authentication and secure user data storage, we will enhance security by integrating advanced measures such as encryption protocols, intrusion detection systems, and secure communication protocols to mitigate the risks associated with data protection. For future large-scale user studies, we will conduct appropriate statistical tests to validate comparisons and ensure statistical significance. We plan to consider the diversity of participants during the recruitment process, ensuring a broad representation across age, gender, experience level, and other relevant demographics. We envision that the advancements of IoHRT will pave the way for the next generation of smart home-care.

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