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RESEARCH ARTICLE

Interactive IIoT-Based 5DOF Robotic Arm for Upper Limb Telerehabilitation

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ABSTRACT Significant advancements in contemporary telemedicine applications enforce the demand for effective and intuitive telerehabilitation tools. Telerehabilitation can minimize the distance, travel burden, and costs between rehabilitative patients and therapists. This research introduces an interactive novel telerehabilitation system that integrates the Industrial Internet of Things (IIoT) platform with a robotic manipulator named xARm-5, aiming to deliver rehabilitation therapies to individuals with upper limb dysfunctions. With the proposed system, a therapist can provide upper limb rehab exercises remotely using an augmented reality (AR) user interface (UI) developed using Vuforia Studio, which transmits bidirectional data through the IIoT platform. The proposed system has a stable communication architecture and low teleoperation latency. Experimental results revealed that with the developed telerehabilitation framework, the xArm-5 could be teleoperated from the developed AR platform and/or use a joystick to provide standard upper limb rehab exercises. Besides, with the designed AR-based UI, a therapist can monitor rehab/robot trajectories along with the AR digital twin of the robot, ensuring that the robot is providing passive therapy for shoulder and elbow movements.

INDEX TERMS Telerehabilitation, upper limb, end effector, IIoT, augmented reality, teleoperation, robotic arm.

NOMENCLATURE

AR	Augmented Reality.
UI	User Interface.
IIoT	Industrial Internet of Things.
IT	Information Technology.
HTTPS	Hypertext Transfer Protocol Secure.
VR	Virtual Reality.
PLM	Product Lifecycle Management.
TCP	Transmission Control Protocol.
RTU	Remote Terminal Unit.
DH	Denavit–Hartenberg.
HTM	Homogeneous Transformation Matrix.
PI	Proportional Integral.
SDK	Software Development Kit.

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I. INTRODUCTION

Stroke affects over 750,000 individuals each year [1], and most stroke survivors have impairments in varying degrees of their motor function [2]. After a stroke, the most frequent problem is upper extremity dysfunction, including muscle weakness, spasms, and multi-joint coordination problems [3]. Approximately 85% of stroke survivors will experience upper extremity dysfunction in the early stages [4]. Patients with motor dysfunction lose their self-care and employment capacities, decrease their life quality, and bring a heavy economic burden on their families [5]. It is critical to focus on rehabilitating the upper limb to enhance the quality of life that is compromised after a stroke. A physical or occupational therapist is usually assigned to stroke patients during hospitalization. The therapist can only train one patient at a time, leading to the high demand for therapists [6]. Recent studies have shown that robot-assisted therapies can help recover from neurological diseases like stroke. Compared to humans, robots are reliable and consistent at repeating tasks [7]. A consistent and successful rehabilitation process can be achieved with robot-assisted treatment. Furthermore, a rehabilitation robot can provide reliable information about the functional assessment of patient recovery [8].

The contemporary era has seen a surge in the development of first-generation robot-assisted rehabilitation equipment and methods, which began in the 1960s [36]. Different configurations of exoskeleton robots are developed based on their purpose: rehabilitation, haptics, assistive device, teleoperations, and power augmentation [37]. Existing exoskeleton-type therapeutic robots need to evaluate carefully since it is directly attached to the human body [38]. Moreover, most exoskeleton robots do not have a link-length adjustment mechanism to accommodate a wide range of users with different heights/weights. Furthermore, using/wearing exoskeleton-type robots for rehabilitating patients with spasticity is often challenging. Compared to the exoskeleton robots for rehabilitation, the end-effector therapeutic robots are easier to use, safe, and suitable for rehabilitation therapy [39] to provide upper extremity rehabilitation through end-point exercises.

Telerehabilitation uses information technology (IT) to provide individuals with physical and/or cognitive disabilities with remote assistance and evaluation [9]. The remote operating system for rehab in medical applications can minimize the distance between rehabilitative patients and therapists, allowing for better connection. This will increase the understanding of therapists on the recovery of patients with recuperation and the range of possible applications. The importance of using telerehabilitation appears to improve economic barriers by reducing the cost and time of traveling [10]. Another benefit of telerehabilitation is that a single therapist could train numerous patients at once by having each patient interact with their robotic device at their remote location [11].

In this paper, we have developed a system for upper limb telerehabilitation using an interactive IIoT control-based robotic manipulator. This system is a cross-platform, collaborative, and comprehensive telerehabilitation system that leverages the power and reliability of the ThingWorx cloud platform to deliver a cutting-edge experience for patients and providers [34]. It uses the secure internet HTTPS protocol provided by the ThingWorx server. Using Vuforia Studio, we have designed a user-friendly graphical user interface with virtual buttons to control and visualize the robotic arm remotely [35]. Its robust control architecture allows a therapist to conduct therapy sessions remotely. This interactive approach encourages patients to receive upper limb rehabilitation therapy from the comfort of their own homes, which is especially important during the Covid-19 pandemic.

Furthermore, it provides a crucial platform for storing rehabilitation-related data and exercise results to analyze patients' recovery. A robust control architecture allows patients with upper extremity dysfunctions to conduct therapy remotely; thus, no expert must attend every rehabilitation session.

This paper is organized as follows: Section II represents the related work on robotic telerehabilitation by utilizing virtual reality environments. Section III focuses on the overview of the system architecture of telerehabilitation and its subsystems' communication, workspace, theoretical analysis of forward kinematics, and dynamics of the robotic arm. Section IV is dedicated to the experimental setup. Section V discusses the experiments and results. Section VI provides the conclusion.

II. RELATED WORKS

Telerehabilitation, also known as teletherapy, uses information and communication technologies such as the telephone, video conferencing, and virtual reality to help patients receive medical services and therapies remotely [15], [24], [25]. The technological capabilities of telerehabilitation are typically achieved through video conferencing and include the ability for therapists to see patients' movements while performing rehabilitation tasks. Typically, therapists in charge of telerehabilitation programs use telephone technology at the start of implementation [14]. The telerehabilitation implementation project has become more sophisticated since the invention of the Internet in the 2000s. When the Internet is upgraded with high-speed wireless, the usefulness and efficiency of telerehabilitation implementation for stroke patients are expected to improve [10].

In recent decades, many research groups have been developing sophisticated robotic devices that can be operated remotely and be worn by a person to manage the remote slave robots [12], [13]. Zhang et al. [26] developed a telerehabilitation system based on an exoskeleton device that can be controlled remotely as a slave device by a therapist through a master device, but the therapist can only monitor the patient's status visually via a web camera. Weiss et al. [27] proposed a telerehabilitation system for passive and assisted wrist and finger training based on an end-effector device. The system includes a data gathering and communication module for remote monitoring, visual biofeedback, and gaming applications for the patient. The system contains rehabilitation games as well as patient feedback on therapeutic progress.

Virtualization technologies are used by robotic devices to create a virtual environment that mimics the real environment. Virtual reality therapy for stroke rehabilitation is still in its early stages [28], [29]. Virtual reality devices are frequently designed as interactive games or virtual gloves [30] and offer games that require physical movement of the hand to negotiate obstacles and interact with a virtual balloon and the fingers to release a ball to strike a target. Other virtual reality training methods [29], [31] include pointing task training, which teaches patients how to use their injured arms to achieve goals. Virtual reality tracking technology enables qualitative and quantitative evaluation of stroke rehabilitation activities that would otherwise be impossible to assess in home-based exercises. Pedreira da Fonseca et al.,

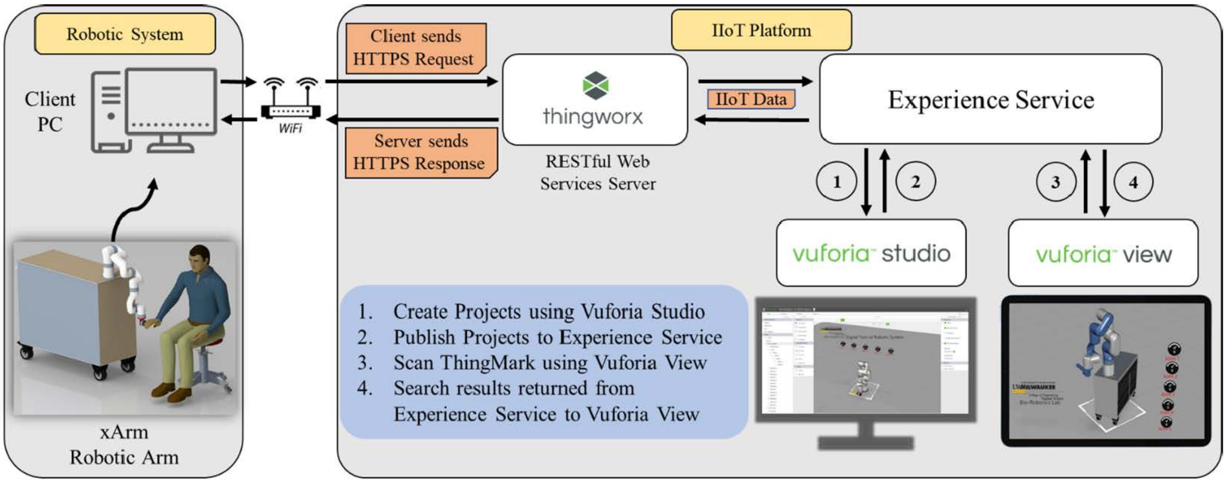

FIGURE 1. System architecture of the proposed telerehabilitation.

2017, [16] compare the therapeutic effect of virtual reality (VR) to traditional physiotherapy in the rehabilitation of gait balance and the occurrence of falls following a stroke using a computerized system. Berg et al. [17] investigated the impact of a caregiver-mediated exercise program initiated in the hospital plus e-health on self-reported mobility using a virtual user interface. Machine learning research using virtual reality technology could develop intelligent decision support systems that detect important assessment characteristics and summarize patient-specific analyses using reinforcement learning [33]. Virtual reality generally creates a safe and controlled virtual environment that can be applied to real-life situations.

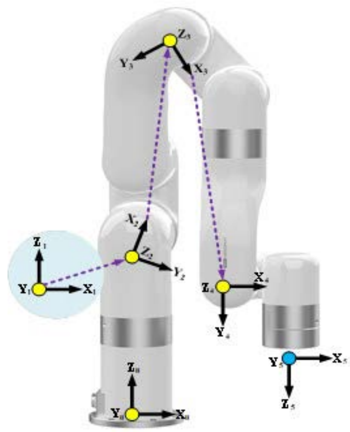

FIGURE 2. Joint coordinate definition of the robotic arm.

III. OVERVIEW OF THE SYSTEM ARCHITECTURE

A. METHODOLOGY

As shown in Fig. 1, the control architecture of the proposed telerehabilitation system is mainly composed of two subsystems: The robotic system, which includes a robot, in this case, a xArm-5 robot developed by Ufactory, and the IIoT Platform. Both these subsystems communicate through the internet. The robot is connected with a Client PC (Windows Computer) and delivers various telerehab therapies' trajectories (e.g., exercises) when it receives excises' commands via the IIoT platform. IIoT platform contains ThingWorx, Experience Service, Vuforia Studio, and Vuforia View. The ThingWorx acts as a bridge for the IIoT platform to transfer data between the robotic system and the augmented reality (AR) application through Vuforia View app. The client PC and ThingWorx communicate bidirectional using Thing-Worx server secure HTTPS protocol. The client PC sends HTTPS requests to the ThingWorx server, and the ThingWorx server sends HTTPS response back to the Client PC. The Experience Service is part of the ThingWorx and contains IIoT data regarding therapies' joint angle parameters. In this study, the user interface (UI) was built for telerehabilitation therapies using Vuforia Studio and published that UI to experience services—it could be accessed from the android/iOS platform. The Vuforia View app is connected with the experience services of ThingWorx, and it sends the IIoT data to the robotic system after interacting with Vuforia View UI.

B. IIoT PLATFORM

The ThingWorx is the Industrial Internet of Things (IIoT) platform developed by PTC Inc. ThingWorx provides a platform for structuring and organizing data for industrial IoT, such as Product Lifecycle Management (PLM), 3D CAD models, etc. ThingWorx offers connectivity, analytics, and tools to create apps and AR experiences. The "Thing Model" uses real-time connectivity solutions to represent physical entities as virtual ones [40]. Mashups can deliver information from the ThingWorx model to a website [41]. ThingWorx's architecture shows industrial use. "Thing Model" consists of Thing, Thing shape, Thing template, Service, Event, and Subscription. This connected system relies on collecting and analyzing operational data, reducing risk in operations such as in-home/industrial utilities, smart cities, healthcare, and factories.

TABLE 1. Modified denavit-hartenberg parameters for xArm 5.

i	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	0	L_1	θ_1
2	-π/2	0	0	$\theta_2 + {}^0\theta_2$
3	0	L_2	0	$\theta_3 + {}^0\theta_3$
4	0	L_3	0	$\theta_4 + {}^0\theta_4$
5	-π/2	L_4	L_5	θ_5

TABLE 2. Dimensional parameters of xArm 5.

Parameters	Values
L_1	0.267 m
L_2	0.289 m
L_3	0.351 m
L_4	0.076 m
L_5	0.097 m
${}^0\theta_2$	-1.3849 rad
${}^0\theta_3$	2.7331 rad
${}^0\theta_4$	-1.3483 rad

C. ROBOTIC ARM

For an experimental demonstration of telerehabilitation, a robotic manipulator named xArm 5 is used, as shown in Fig. 2. The xArm 5 is a five-degrees of freedom (DoF) robotic arm with blushless servos, harmonic reducers, 6-axis force-torque sensor, and position repeatability of ± 1.0 × 10-4 m [18]. It uses Modbus-TCP and Modbus-RTU communication protocols for the robotic arm and end-effector, respectively [18]. The total workspace area of xArm 5 is 0.7 m [18]. In our study, xArm's Python SDK is used to control the xArm 5 for advanced functionality.

1) KINEMATICS OF ROBOTIC ARM

Using the robot's joint angles, the position and orientation of the robot end-effector can be determined by solving the forward kinematics. The xArm-5 robot's kinematic model is developed using modified Denavit-Hartenberg (DH) notations. Table 1 summarizes the modified DH parameters corresponding to the location of the link frames in Fig. 2 [19].

Here, I represents the joint, α_{i-1} is the link twist, a_{i-1} corresponds to link length, d_i stands for link offset, θ_i is the joint angle(radian), ${}^0\theta_i$ represents the offset of the joint angle θ_i, and L_i represents the length of i of xArm 5. These ${}^0\theta_i$ and L_i dimensional parameters [19] are presented in Table 2.

The general form of a link transformation that relates frame i relative to the frame $i-1$ [20] is:

$$ {}^{i-1}_{i}T = \begin{bmatrix} {}^{i-1}_{i}R^{3\times3} & {}^{i-1}_{i}P^{3\times1} \\ 0^{1\times3} & 1 \end{bmatrix} \quad (1) $$

where, ${}^{i-1}_{i}R$ is the rotation matrix that describes frame i relative to frame $i-1$ and can be expressed as the following:

$$ {}^{i-1}_{i}R = \begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 \\ \sin\theta_i\cos\alpha_{i-1} & \cos\theta_i\cos\alpha_i & -\sin\alpha_{i-1} \\ \sin\theta_i\sin\alpha_{i-1} & \cos\theta_i\sin\alpha_{i-1} & \cos\alpha_{i-1} \end{bmatrix} \quad (2) $$

And ${}^{i-1}_{i}P$ is the vector that locates the origin of frame i relative to frame $i-1$ and can be expressed as the following:

$$ {}^{i-1}_{i}P = \begin{bmatrix} a_{i-1} & \sin\alpha_{i-1}d_i & \cos\alpha_{i-1}d_i \end{bmatrix} \quad (3) $$

Using Eqs. (1), (2), and (3) the individual homogeneous transfer matrix (HTM) that relates two successive frames, we got

$$ {}^0_1T = \begin{bmatrix} \cos\theta_1 & -\sin\theta_1 & 0 & 0 \\ \sin\theta_1 & \cos\theta_1 & 0 & 0 \\ 0 & 0 & 1 & L_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4) $$

$$ {}^1_2T = \begin{bmatrix} \cos(\theta_2 + {}^\circ\theta_2) & -\sin(\theta_2 + {}^\circ\theta_2) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -\sin(\theta_2 + {}^\circ\theta_2) & -\cos(\theta_2 + {}^\circ\theta_2) & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5) $$

$$ {}^2_3T = \begin{bmatrix} \cos(\theta_3 + {}^\circ\theta_3) & -\sin(\theta_3 + {}^\circ\theta_3) & 0 & L_2 \\ \sin(\theta_3 + {}^\circ\theta_3) & \cos(\theta_3 + {}^\circ\theta_3) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6) $$

$$ {}^3_4T = \begin{bmatrix} \cos(\theta_4 + {}^\circ\theta_4) & -\sin(\theta_4 + {}^\circ\theta_4) & 0 & L_3 \\ \sin(\theta_4 + {}^\circ\theta_4) & \cos(\theta_4 + {}^\circ\theta_4) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (7) $$

$$ {}^4_5T = \begin{bmatrix} \cos\theta_5 & -\sin\theta_5 & 0 & L_4 \\ 0 & 0 & 1 & L_5 \\ -\sin\theta_5 & \cos\theta_5 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (8) $$

The homogenous transformation matrix that relates frame 5 to frame 0 can be obtained by multiplying individual transformation matrices that result in the generic form Eq. (9).

$$ {}^0_5T = \begin{bmatrix} {}^0_1T \cdot {}^1_2T \cdot {}^2_3T \cdot {}^3_4T \cdot {}^4_5T \end{bmatrix} \quad (9) $$

2) PI CONTROL

The proportional-integral controller (PI controller) is the most commonly used feedback-based controller control system [21]. In this study, a PI controller has been implemented for its ease in design and precise computation. Here, the PI control approach used for preliminary testing and the joint toque command of the xArm-5 can be expressed by the Eq. (10) [20]:

$$ \tau = K_P(\theta_d - \theta) + K_I \int (\theta_d - \theta)\,dt \quad (10) $$

where, $\theta_d, \theta \in \mathbb{R}^5$ are the vectors of desired and measured joint angles respectively, K_P, K_I are the diagonal positive definite gain matrices, $\tau \in \mathbb{R}^5$ is the generalized torque vector. Error vector E can be expressed by Eq. (11):

$$ E = \theta_d - \theta \quad (11) $$

Therefore, Eq. (10) can be re-formulated as an error equation:

$$ \tau = K_P E + K_I \int E dt \quad (12) $$

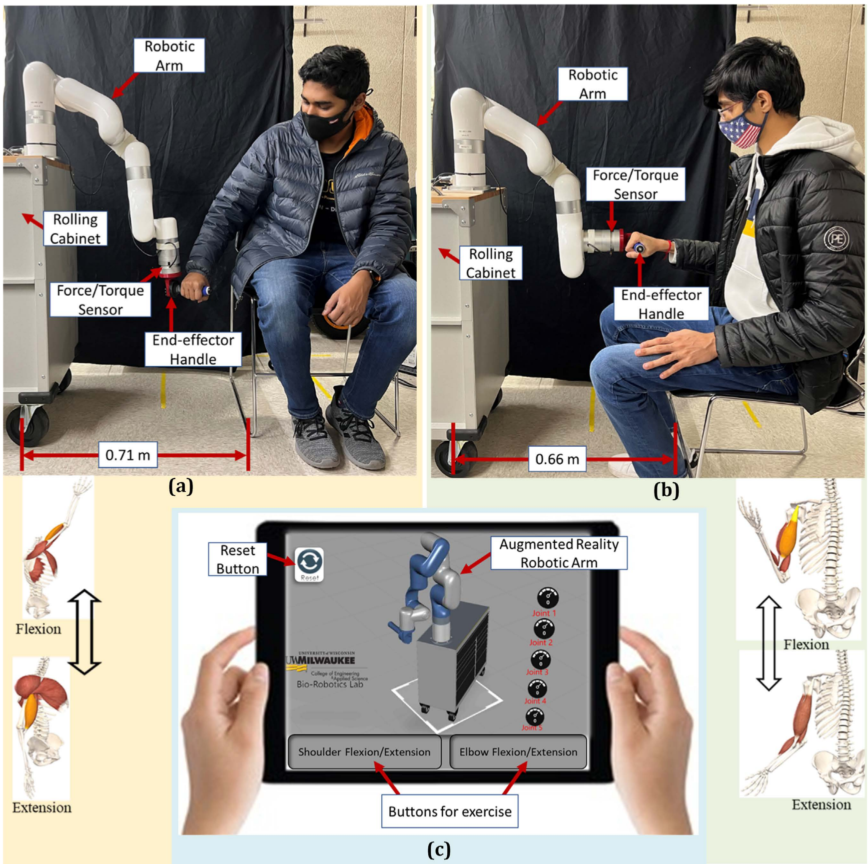

FIGURE 3. Experimental setup for telerehabilitation. (a) Shoulder flexion/extension configuration of the end-effector robotic arm. (b) Elbow flexion/extension configuration of the end-effector robotic arm. (c) Augmented reality user interface created via Vuforia studio.

The relation Eq. (12) is decoupled, therefore individual torque commands for each joint can be expressed by Eq. (13)

$$\tau_i = K_{P_i} e_i + K_{I_i} \int e_i dt \tag{13}$$

IV. EXPERIMENTAL SETUP

The functionality of the developed interactive IIoT-based end-effector robotic arm for upper limb telerehabilitation was validated via experiments. Informed consent was obtained from all subjects for both study participation and publication of identifying information/images. The study protocol (UWM IRB# 20.187) has been reviewed by the University of Wisconsin Milwaukee IRB and approved as minimal risk Expedited under Category 1b as governed by 45 CFR 46.110. The experimental setup is depicted in Fig. 3 and 4. The xArm robotic arm system is mounted on the rolling cabinet, which lets the robotic arm system move and take remote places to provide telerehabilitation. Experiments were conducted with healthy male human subjects (age: 23–35 years, height: 1.60–1.80 m, weights: 51–110 kg) to provide a passive mode of telerehabilitation. This includes passive shoulder flexion/extension (Fig. 3a), and elbow flexion/extension (Fig. 3b). Subjects sat on the chair at a distance of 0.71 m and 0.66 m from the rolling cabinet for the shoulder extension/flexion and elbow extension/flexion experiments, respectively. Since it is telerehabilitation, a scenario was made by putting a robotic system in a separate room with subjects and providing passive therapies to subjects by sending joint angle parameters to the Client PC of passive therapies through iPad using the Vuforia View app or joystick. Figure 3c presents the UI of the Vuforia View app, and by interacting with different buttons on UI, the xArm robotic arm performs various exercises. Also, we were able to monitor exercise trajectories on AR xArm robotic arm in Vuforia View by receiving parameters from the robotic system over ThingWorx-experience services. In the proposed experimental setup, subjects held an end-effector handle of the xArm robotic arm. Figure 4a shows the operator side where the human-robot interaction can be monitored and controlled through the joystick or Vuforia view application and a real-time video session. Figure 4b shows the communication and data capture devices which include a camera and a Kinect sensor to examine the human upper limb during the rehabilitation exercises.

V. RESULTS AND DISCUSSION

The proposed system can provide different telerehabilitation exercises such as passive rehab exercises using pre-determined trajectory or real-time recorded trajectory,

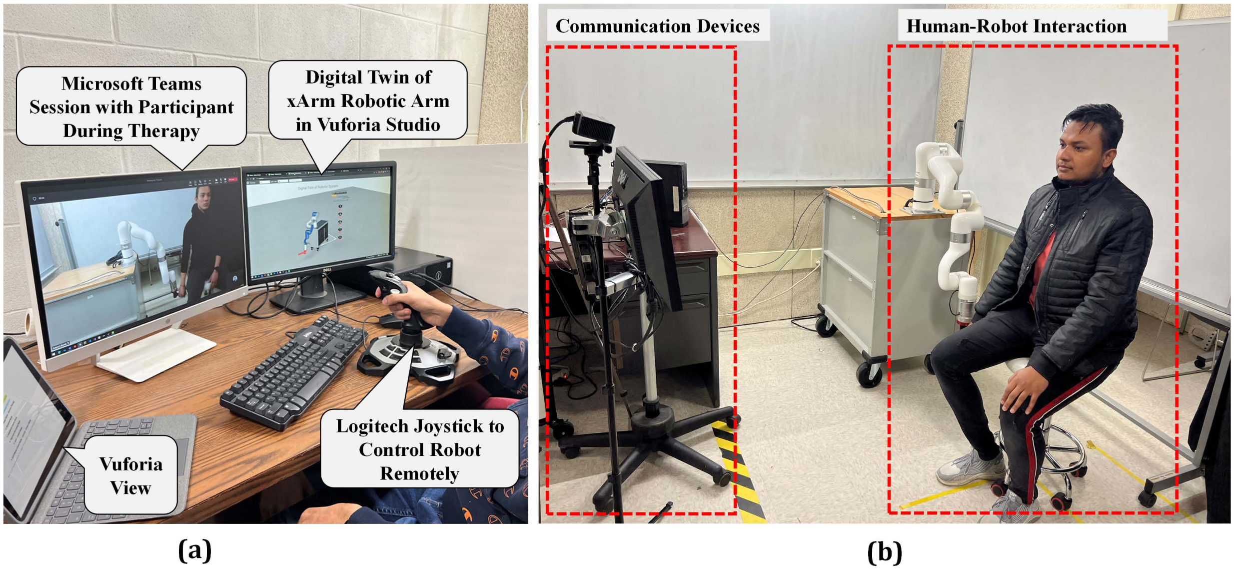

FIGURE 4. (a) The operator side, where human-robot interaction can be monitored and controlled using a joystick or the Vuforia view application (b) Communication and data capture devices.

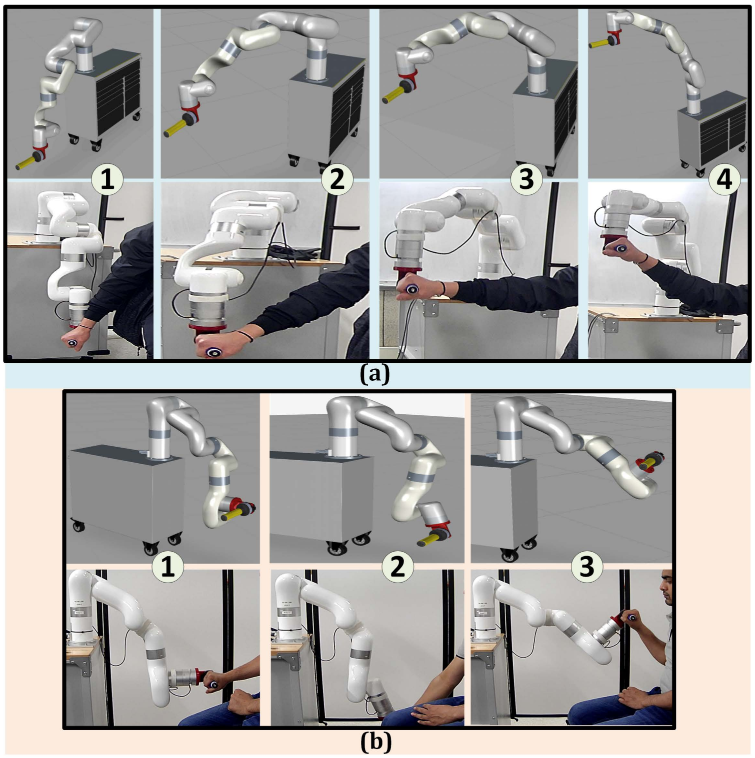

FIGURE 5. Monitoring (a) shoulder joint flexion/extension (b) elbow joint flexion/extension movement on AR robotic arm.

resistive rehab exercises using impedance control, and interactive one-on-one real-time telerehabilitation exercises. The system also has a teaching mode to generate different trajectories manually and provide different exercises. Participants' shoulder and elbow flexion/extension motion is controlled via teleoperation in the experiment. Experimental results were achieved with the xArm robotic arm, as shown in Figures 5, 6, and 7.

For shoulder flexion/extension, the participant sat in position by holding an end-effector handle of the robotic arm as shown in Fig. 3(a). The operator pressed the 'shoulder flexion/extension' button on Vuforia view UI (Fig. 3c) to perform the pre-determined movement. In this exercise, the robotic arm carried the subjects' limbs from one point to another in the sagittal plane, as illustrated in Fig. 3. Cartesian representation (Fig. 6a) shows the end-effector in

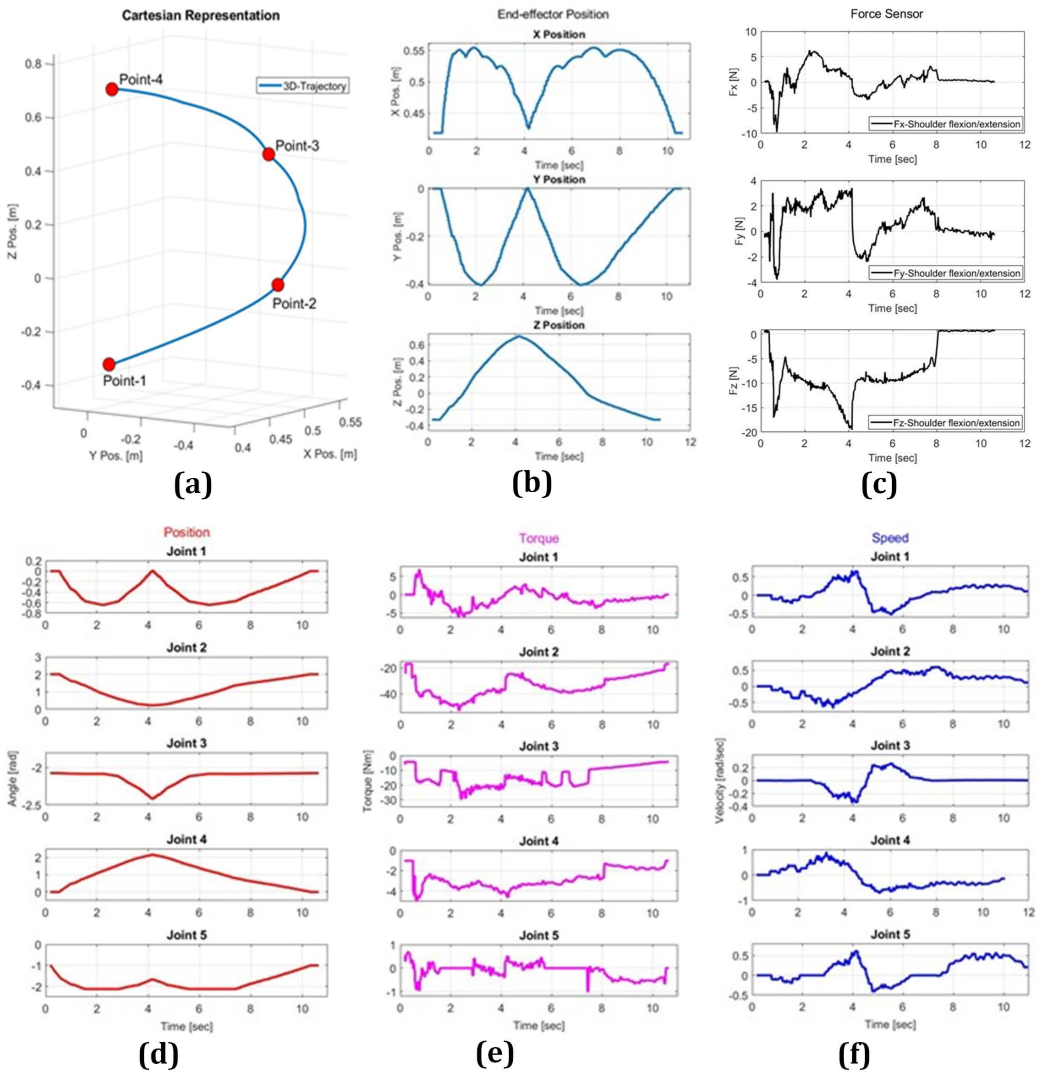

FIGURE 6. **(a) Cartesian representation while shoulder joint flexion/extension movement (b) Cartesian trajectory tracking of the xArm robotic arm (c) Force on the end effector while shoulder joint flexion/extension movement (d) Joint angles, (e) torques, and (f) speed observation while shoulder joint flexion/extension movement.**

three-dimensional space, where the participants' limb was moving from extension to flexion (Point 1-4) and flexion to extension (Point 4-1). The end-effector position (Fig. 6b) shows the cartesian trajectory tracking of the xArm robotic arm in terms of the x, y, and z positions.

The movement of the AR robotic arm was monitored, and at the same time, the data was collected. Fig. 5a shows how therapists can monitor exercise on AR robotic arm through the Vuforia View app while shoulder joint flexion/extension motion. Different instances were taken as same point 1-4 shown in Fig. 6a cartesian representation. By observing the motion of the AR robotic arm, the therapist can determine whether the participants' limb is moving correctly. The joint angles, torques, and speed of each joint are plotted in Fig. 6 using collected data. It can be seen from Fig. 6d that joints 1-4 and 5 started moving at the specific initial angles of 0 rad, 2 rad, −2.07 rad, 0 rad, and −1.0 rad, respectively. From the initial position of the robotic arm's end-effector to the final position, the participants' limb imposed most of the load on joints two and three, shown in Fig. 6e, where the load is expressed in terms of torque. The speed fluctuations during the robotic arm's moment due to the PI control's switching frequencies can be observed from Fig. 6f. It can be seen in Fig. 6c that the participants' limbs exerted most of their force along the z-axis due to the end-effector of the robotic arm moving mostly in the cartesian z-direction.

Teleoperation through a joystick was used to control the participant's elbow flexion and extension motions. The elbow flexion/extension motions are similar to pulling or pushing an object. To perform this exercise, the participant took the position shown in Fig. 3b, and the operator remotely passed commands through the joystick. In Fig. 7 plots, it can be seen that joint 2, 3, and 4 positions were changed throughout the initial and final motion. The participant applied the maximum load

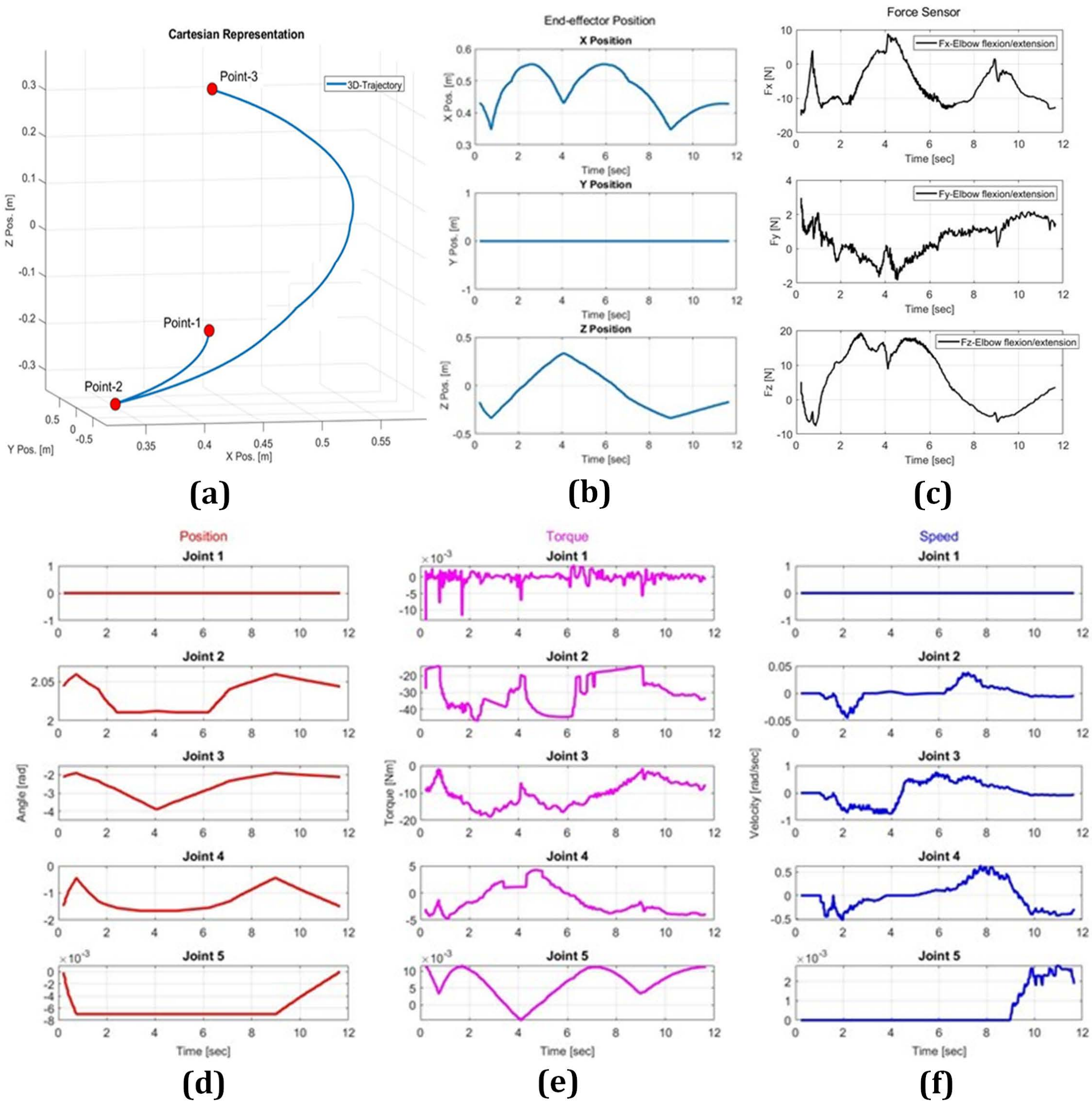

FIGURE 7. **(a) Cartesian representation while elbow flexion/extension movement (b) Cartesian trajectory tracking of the xArm robotic arm (c) Force on the end effector while elbow flexion/extension movement (d) Joint angles, (e) torques, and (f) speed observation while elbow flexion/extension movement.**

to joints 2 and 3. Fig. 5b depicts how a therapist can monitor the movement of an AR robotic arm using the Vuforia View app, while elbow moves and different instances were taken as the same points 1-3 as cartesian representation in Fig. 7a. The ThingWorx AlwaysOn protocol is used by SDK for communication. A binary protocol, ''AlwaysOn'' uses WebSockets as its transport mechanism. This protocol permits continuous WebSocket connections that can easily operate by a firewall. The main advantage is that it allows two-way, lower-input latency communication between the device and platform [42]. The robotic system and IIoT platform experienced a latency of around 0.16s in this study's experiments. While the proposed IIoT and augmented reality-based framework promises a stable control system for human-robot collaboration, there should be a continuous and stable connection to utilize the framework. The system becomes unstable and inoperable if the connection is lost.

VI. CONCLUSION

This work intended to utilize an interactive IIoT-based teleoperated architecture where a therapist can perform pre-determined exercises remotely while monitoring the trajectory of an augmented reality robotic arm. The proposed framework was built using several cutting-edge technologies, including the PTC ThingWorx IIoT platform, the Vuforia Studio Augmented Reality platform, the PTC ThingWorx experience services, and the Vuforia View app for iPad. Experimental results validated that the developed IIoT and augmented reality-based framework for human-robot collaboration can be used for telehealth applications such as telerehabilitation. The current methods of providing rehabilitation therapy require patients to visit a clinic/rehab center for each therapy session. A therapist can only train one patient at a time, leading to a high demand for therapists. Furthermore, the COVID-19 pandemic has affected all aspects of health care, including rehabilitation care for post-stroke patients. Telerehabilitation can address this issue. The developed telemanipulation framework for human-robot collaboration can be used to provide various telerehabilitation exercises to individuals with upper-limb impairment. Performing experiments with stroke participants and integrating machine learning and AI will be the future direction to provide patient-specific therapy based on the longitudinal data of the patients.

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