August 2022

Development of an Upper Limb Telerehabilitation System

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DEVELOPMENT OF AN UPPER LIMB TELEREHABILITATION SYSTEM

by

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A Thesis Submitted in

Partial Fulfillment of the

Requirements for the Degree of

Master of Science

in Engineering

at

The University of Wisconsin-Milwaukee

August 2022

ABSTRACT

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The University of Wisconsin-Milwaukee, 2022
Under the Supervision of Professor Mohammad Habibur Rahman

Upper limb dysfunction (ULD) is common following a stroke, spinal cord injury, trauma, and occupational accidents. Post-stroke patients with ULD need long-term assistance from therapists for their rehabilitation, which generally occurs at the hospital or outpatient clinic. Travel and transportation are significant factors that prevent patients from receiving adequate therapy, often leading to long-term disability. A home-based rehabilitation device providing essential arm movement therapies can significantly ease this rehabilitation program. In this research, we developed an end-effector type Desktop-Mounted Rehabilitation Robot (DMRbot) with a minimum viable design to cover the full range of human upper limb (UL) workspace to provide an essential UL rehab exercise. PTC's Industrial Internet of Things (IIoT) platform is used in this study to provide home-based rehabilitation therapies for individuals with ULD remotely. Remote rehabilitation is pragmatical because of the negligible latency (expedited through cloud services deployment by ThingWorx) and stable communication structure. With the developed telerehabilitation framework, an operator can teleoperate the DMRbot to deliver UL exercises via an Augmented Reality (AR) based graphical user interface (GUI), a virtual joystick. This AR, platform communicates bidirectionally with the robot using ThingWorx IIOT. The developed

telerehabilitation system also allows therapists to administer passive rehabilitation therapy using a physical joystick. This study leverages the digital twin structure, facilitated by Vuforia studio, to visualize the physical robot motions happening in remote places. Experiments were conducted to validate the novel telerehabilitation framework to provide remote therapy using the developed DMRbot. The result show that the DMRbot can be successfully controlled from the Vuforia studio AR platform and with a joystick to provide UL rehab exercises in 2D and 3D planes.

Keywords: IIoT, Digital Twin, Home-based, Upper-limb Rehabilitation, Telerehabilitation, An end-effector robot, ThingWorx, Vuforia Studio.

To

My parents & brothers

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

First and foremost, I would like to express my gratitude to the All-Powerful Allah (SWT), who provides me the knowledge, courage, and endurance necessary to do my thesis work. I want to express my respect to my family, who, although living far away, helped me become brave and strong via their compassion and unending moral support. My sincere gratitude goes out to Professor Mohammad Habibur Rahman, who recommended me for the MS program in mechanical engineering at the University of Wisconsin Milwaukee and gave me the opportunity to do my research work under his kind supervision. He always helped and pointed me in the right direction so I could learn. I'm hoping that the connection we made will endure for a very long time.

I am glad to work with Dr. Rahman and all BioRobotics Lab members for my research in BioRobotics Lab. I also want to thank Dr. Ilya Avdeev, Dr. Inga Wang, and Dr. Md Rasedul Islam for accepting my request to be on the master's comprehensive exam committee. I'm thankful to Javier Dario Sanjuan De Caro, who patiently listened to my research problems, helped me find a solution, and gave me good advice.

Lastly, I'd like to thank my wife, Busrat Tabassum for her incredible patience, sacrifice, support, and encouragement during this project. Without her consistent support and guidance, this work could not have been done.

CHAPTER 1

INTRODUCTION

Approximately 15 million individuals [1] globally suffer from neurological diseases, such as strokes. In the USA, approximately 750,000 persons are affected by stroke [2], leaving most survivors with varying degrees of motor dysfunctions [3]. At the same time, 85% of stroke survivors who suffer from hemiparesis live with acute arm impairment [4]. As a result, 60% of individuals with upper limb hemiparesis start to have long-term functional limitations, which compel them to degrade their life standards [5], [6]. This poor life quality includes losing work abilities and failing self-care. These characteristics have a significant social and economic impact on their families and society [7], [8]. The recovery of the upper limb (UL) can play a significant role in reinstating the quality of life of the individuals. Repetitive functional motion is an effective therapy for stroke patients that improves their rehabilitation [9]. Physical therapy is the traditional technique of rehabilitation for stroke patients. Traditional rehabilitation focuses on rehabilitative exercises, in which the patient performs a series of bodily motions under the guidance of a trained therapist. However, there is a scarcity of physical therapists and caregivers, and insurance coverage frequently limits the length of time patients spend in treatment [7], [10]. As a result, patients are not receiving enough dose of therapy, which is a crucial aspect of neurological recovery from injuries. So, there is a massive demand for cost-effective treatment approaches that can assist regain arm function. Robots tend to help recover from the upper/lower limb dysfunctions (ULD) derived from a neurological disorders, which have been manifested in recent studies [10], [11, 12]. Many scholars have set their sights on developing medical rehabilitation devices [13]. Robots can provide repetitive therapy/movements to the impaired limbs [14]. Compared to traditional therapeutic exercises by the therapist, robot-assisted rehabilitation takes less labor from the

therapist. It provides an extensive toolkit for evaluating the recovery state of the patient based on the gathered physical and biological data [15]. Robotic rehabilitation treatments increase rehabilitation outcomes and allow a physical therapist to handle many patients at the same time [16]. Additionally, this modern therapy facilitates a quantitative recording of data attached to recovery progress. Robots can provide passive, active, and active-assistive therapies to the impaired limbs [17], [18].

In general, upper limb robotic devices are subdivided into two types end-effector type and exoskeleton type robots [19]. Exoskeleton robots are designed to be worn on human limbs. The design of this type of robot mimics human anatomical joints and the length of limb segments. Due to the multiple "bundling" of the exoskeleton robot and the upper limbs, the patient cannot detach from the robot quickly if unexpected danger occurs [20]. Many exoskeleton robots are designed to provide rehabilitation therapy in a full range of UL motion. The rehabilitation therapies include joint-based and end-point-based passive, active-assisted, and resistive therapies [21], [22], [23]. However, these exoskeleton robots are costly, structurally complicated, and lack mobility.

In contrast, end-effector type rehabilitation robots are designed to hold the users at a single point, usually at the wrist or forearm. The primary advantage of end-effector type devices over exoskeletons is their simplicity in design and manufacturing. End-effector robots are more compact and lightweight than other robots, and their construction is easier to build. Furthermore, because of the single-point interaction between the two entities, end-effector type devices are the most prevalent assistive device [24], [25], [26]. An end effector-type robot is easy to install in a patient's home because of its simple structure and is a low-risk factor. Due to the COVID-19 pandemic, all patients with disabilities experienced difficulty in completing their rehabilitation

exercise/treatment because of the limited/no access to appropriate rehabilitation facilities and services imposed by the social distance. Telerehabilitation has the ability to alleviate this issue.

Telerehabilitation is a prominent method to provide health care that allows medical rehabilitation care to people from remote areas [27]. Telerehabilitation is a term used in healthcare to describe the delivery of rehabilitation services, such as physical and occupational therapy, from a distance. The development of technology, telehealth techniques, and telehealth stroke rehabilitation make telehealth projects easier and allow patients to continue to be cared for at home [28]. In the past few years, information technology (IT) solutions have been developed that allow health professionals to treat patients through teletherapy. The cost for a single session of in-home telerehabilitation compared to conventional home-visit rehabilitation is lower [29], depending on the distance between the patient's home and health care center. Tele-rehabilitation is more cost-effective for health care providers and patients than traditional inpatient or person-to-person rehabilitation [30]. Due to the aging of society and even faster advances in medicine and technology, health care costs are rising quickly. Because of this, cost-effective rehabilitation is a priority and a challenge for both patients and therapists [31].

In the prior study, we developed a 2 Degree of Freedom (DoFs) robot for rehabilitation, but its workspace was restricted in 2D plane. To address this issue, in this study, we have developed a 3 DoFs robot to provide the whole range of upper limb motion in 3D space. In the prior research at BioRobotics Lab at UWM, we also developed a telemanipulation framework using an industrial robot (xArm-5) [105], PTC's IIOT platform and Vuforia studio's AR platform. In this study, we adopted this architecture for telerehabilitation and created a minimal viable product (DMRbot) that can be utilized to deliver therapeutic intervention at home.

1.1 Research Goals and Specific Aims

One of the proposed research goals is to develop an upper-limb rehabilitation training system that is simple to use, inexpensive (cheap), and comfortable to use at home with the least amount of structure. Thus, in this study, we have developed a portable 3 DoFs end-effector rehabilitation robot called DMRbot (desktop mounted rehabilitation robot) that can be utilized simply at patients' homes for UL rehab activities as a minimal viable product. The second goal is to make a novel framework for a collaborative robot (DMRbot) that uses PTC ThingWorx communication for the Vuforia Studio application. The system uses the Hypertext Transfer Protocol Secure (HTTPS) internet protocol provided by the ThingWorx server. The DMRbot allows therapists or operators to administer passive rehabilitation therapy using a graphical user interface (GUI) and a physical joystick. In addition, this project uses the digital twin architecture facilitated by Vuforia studio to visualize the physical robot motions happening in remote places.

The specific aims of this research project are as follows:

Aim 1: *Develop a desktop-mounted rehabilitation robot (DMRbot) a minimum viable therapeutic robot to provide upper-limb rehab exercise.*

Aim 2: *Develop a telerehabilitation framework for telemanipulating the DMRbot for upper-limb rehabilitation.*

Aim 3: *Experiment with healthy human subjects to evaluate the proposed telerehabilitation system for robot-aided passive rehabilitation exercise.*

1.2 Organization of the Thesis

The rest of the thesis is organized in chapters as described below.

CHAPTER 2: Literature Review

This chapter briefly presents the research works on telerehabilitation, and robot-assited telerehabilitation.

CHAPTER 3: Robot-Assisted Telerehabilitation

This chapter descrives different types of upper limb rehabilitation approaches, including; telerehabilitation, neurorehabilitation, robot-assisted rehabilitation, and robot-assisted telerehabilitation.

CHAPTER 4: Development of DMRbot

This chapter describes the DMRbot's design, workspace, capabilities, kinematics, and control.

CHAPTER 5: Digital Twin of DMRbot

This chapter describes the digital twins, digital threads, and a detailed procedure for developing a digital twin of the DMRbot using PTC Vuforia Studio.

CHAPTER 6: Telerehabilitaion Framework

This chapter explains how a telerehabilitation framework was developed through the synergestic integration of PTC ThingWorx-IIOT platform. Vuforia Studio's AR platform, and DMRbot.

CHAPTER 7: Experiments and Results

This chapter describes the experimental setup for the telerehabilitation framework and graphical representation of the results/findings of the experiments.

CHAPTER 8: Conclusions and Future Work

Finally, the Conclusions section of this research summarizes the findings from the research outcomes and suggests directions for further research in the section Recommendations. The potential of this study via further improvement is shown in the future scopes section.

CHAPTER 2

RELATED WORK ON TELEREHABILITATION

Technology advancements have allowed medical personnel to treat patients remotely, and digital innovations have made telerehabilitation possible through real-time communication. The reality technologies are the result of combining the most advanced imaging and computer techniques, and they have the potential to revolutionize several areas of the healthcare industry, including physical rehabilitation and remote surgery [32], [33], [34]. Telerehabilitation is a new health care delivery technique that allows medical rehabilitation therapy to be supplied from a distance by utilizing telehealth to provide remote health care [27]. Telerehabilitation, also known as teletherapy, is the use of information and communication technologies such as the telephone, video conferencing, virtual reality, and mixed reality to help patients get medical services and therapies from a remote distance [35], [36],[37] . The first scientific publication on telerehabilitation was in 1998 [30]. The number of research studies on this area/topic has increased in recent years, most likely owing to rising human demands and the development of exciting new communication and computing technology.

Technologies enabling home-based rehabilitation have the potential to save money while improving patients' access to care. Telerehabilitation has been created to care for inpatients, moving them home after the acute phase of an illness in order to minimize hospitalization periods and expenses for both patients and health care providers [30]. Professionals can now treat patients via teletherapy following recent developments in information technology. Several forms of telerehabilitation therapies and their respective intensities and durations have been reported. Telerehabilitation enables the treatment of disorders in their acute phase by substituting the usual face-to-face interaction shown in Figure 2-1 between patient and therapist [38], [39]. In Figure

2-1, a therapist gives a voice command to follow his instruction through a skype call. Also, it can address instances where it is difficult for patients to go to typical rehabilitation facilities that are located distant from their homes. In addition, home rehabilitation may also give patients a comfortable and convenient living environment; therefore, it can reduce the patients' psychological stress.

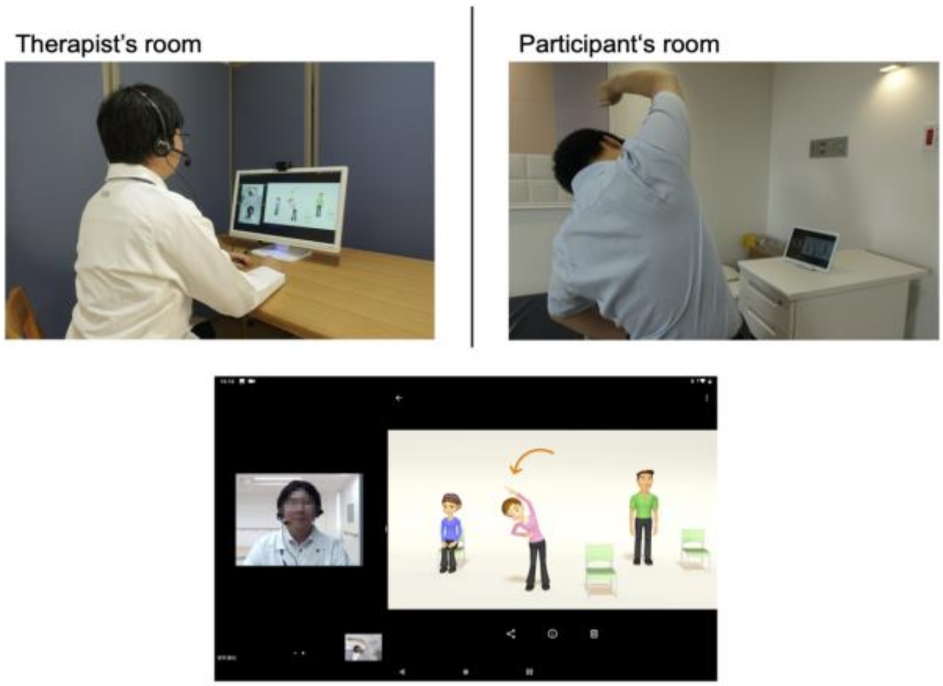


Figure 2-1 Exercise program delivered using the telerehabilitation system [39]

Telehealth interventions use telecommunications and/or virtual environments, such as virtual reality (VR), augmented reality (AR), or mixed reality (MR), to provide healthcare from a remote location. As seen in Figure 2-2 technology like VR and MR equipment is now used to create customized interactive training with better patient motivation [40]. Personalized interactive training with increased patient motivation is now possible by combining techniques such as VR and MR equipment. VR is a technology that creates an immersive, computer-generated world for

the user to experience. The most cutting-edge VR experiences can offer freedom of movement via a virtual world. Special controllers can also be used with the user's hands to improve the VR experience [42], [43].

Figure 2-2 Customized interactive training using combined VR and MR techniques [40]

Mixed reality (MR) is the newest piece of technology in the reality field. Like AR, an MR system will combine the three-dimensional virtual model to generate a holographic image. Additionally, the technology enables the MR user to interact with both the physical environment and the digital content that has been added. The camera with the MR device in conjunction with the user's eyes. It allows the user to manipulate the three-dimensional image ("also known as a hologram") from their perspective [44].

The MR-based approaches are becoming popular for different applications among researchers' day by day as it has potential in many ways. For instance, researchers have used the MR environment to design an interface for human-robot interaction to teleoperate a robot [45], [46].

Researchers also used these approaches to design various robotic control systems. A LEAP Motion Controller and Oculus Rift VR headset were utilized to operate Baxter via MR shown in Figure 2-3 remotely. A person can interact with Baxter by putting on the headset and raising their hands. The LEAP Motion Controller identified the hands and sent data to Java and Unreal Engine. This technology allowed Baxter to be remotely modified by replicating the user's hand movements.

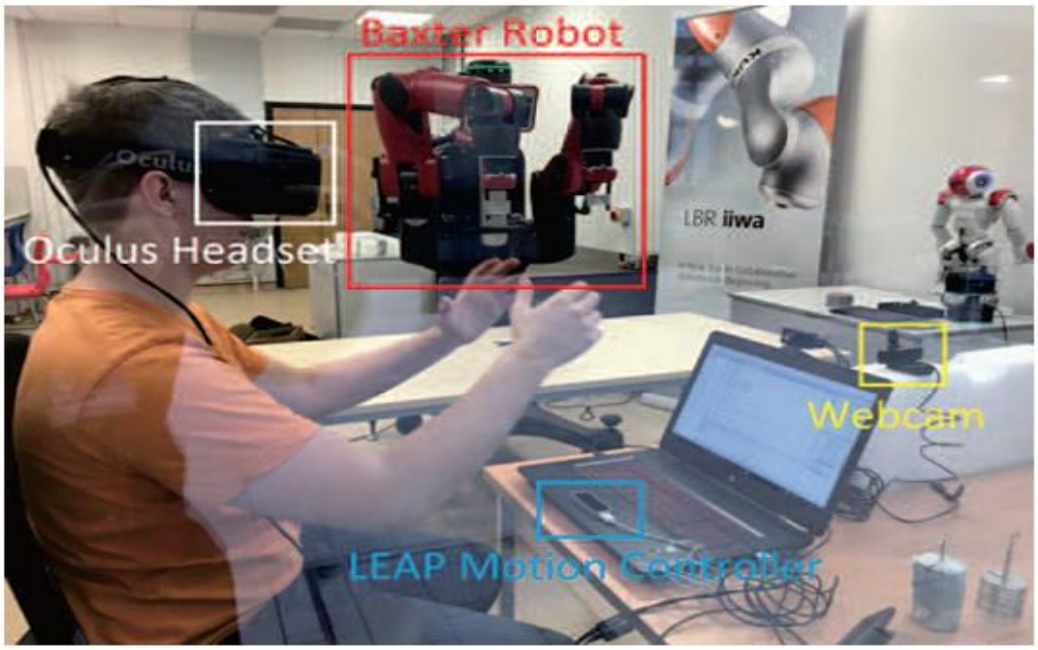


Figure 2-3 MR-based interface for human-robot interaction setup [45]

In one study, researchers developed an interface for human-robot communication using MR for interactive robot manipulation control for mobile platforms [47]. The interface offered tools for robot path planning and visualized it for workers to comprehend robot behavior to ensure safety. The interface was successfully implemented and evaluated on Microsoft HoloLens. In another similar study, researchers used both MR and VR to design workspace for collaborative robots in the industry [48]. Robotic Operating System (ROS) and Unity were utilized to design the system and tested in diverse settings. In another work, researchers presented an interactive control

framework for single and multi-robot systems using MR for various applications [49]. The system allowed interaction with robots by focusing on the visualization of its' objective, and it could relate to any robots and MR interfaces. The presented framework was evaluated experimentally, and the results verified the capabilities of the framework in the MR system.

Researchers are also exploring framework-based approaches to construct generalized systems for different applications. In one study, researchers proposed an open-source framework for a humanoid robot using cross-architecture, which was low cost in computation [50]. The framework was validated via both simulator and telemetry interface, and the result showed that it could be used to design new algorithms. In another study, researchers presented a framework for a collaborative human-robot environment using a commercial manipulator and their unique control method [51]. The framework included a trajectory planning and safety strategy that was evaluated in a factory by exploiting the human worker's experiences. In another study, a few researchers presented a framework for robot-assisted control in human-robot cooperation for a 7-DoF surgical robot [52]. The framework used manual motion to drive the tooltip, a 3D camera-based method to adjust the workspace, calculate optimal instrument orientation, and cartesian interpolation to assure safety. Where in other studies, researchers proposed frameworks for different human-robot collaboration-based applications like industrial cyber-physical systems (CPS) [53], interaction in games (i.e., Rock-Paper-Scissors) [54], and cooperative assembly duties [55].

In the last 15 years, the number and variety of VR applications for rehabilitation have increased significantly, indicating that the study in this area may suggest a new scientific area [26]. Lewis and Griffin (1997) started to look at VR technology in several areas of rehabilitation and concluded that it has much potential in healthcare. Virtual reality tracking technology makes it possible to evaluate both the quality and quantity of stroke rehabilitation activities [56]. Zhang et al. [28]

established a telerehabilitation system based on an exoskeleton device that can be managed remotely as a slave device by a therapist through a master device (see Figure 2-4). The therapist can visually check the patient's status using a web camera. Weiss et al. [29] developed a telerehabilitation device for passive and aided wrist and finger training based on an end-effector device. The system includes therapy games and patient feedback on therapeutic progress. The system integrates a data collection and transmission module for remote monitoring and visual biofeedback for patients.

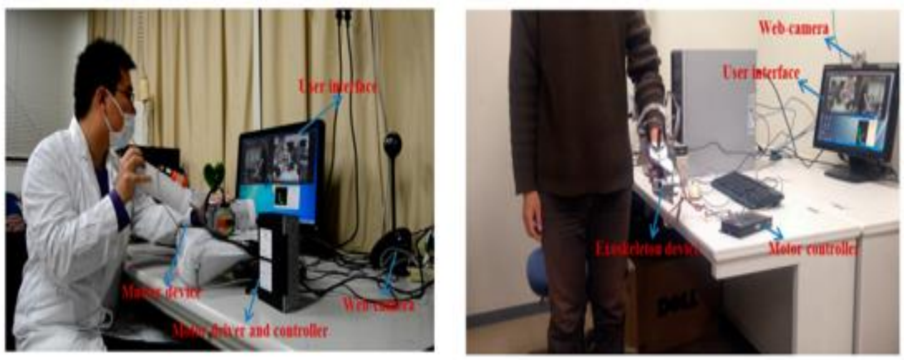


Figure 2-4 Master and Slave side showing Teleoperation and Performance Test for Passive Training [28]

The user's objectives might be shown on the head-mounted display, and feedback could be provided depending on the number of targets fulfilled. MR Rehabilitation (MRR) programs have consistent features. MRR programs teach participants particular actions to improve their physical abilities such as balance, motor control, strength, and/or flexibility. People often use these programs for several weeks, and the length of each session depends on the user's demands [57], [58], [59]. MRR programs can typically recognize user movements because they digitally blend reality and virtuality, and they frequently include the capability to provide automated direction and

feedback. These programs can be used in conjunction with an instructor who provides feedback and direction, but they can also be used autonomously.

The majority of MRR solutions give users the ability to participate in naturalistic rehabilitation activities by utilizing augmented reality or augmented virtuality (AR). The AR helps reduce the amount of "translation" of behaviors that must occur when moving from the training environment to the transfer environment. When users perform physical rehabilitation exercises using the MRR program, they can grasp ordinary items, navigate around typical obstructions, and engage in various everyday activities. Most MRR programs additionally allow users to monitor their limbs while performing tasks, which improves behavioral similarity between training and transfer scenarios [60], [61]. Additionally, MR interfaces can operate with single and multi-robot systems, including industrial manipulators, mobile robots, and unmanned aerial aircraft (see Figure 2-5).

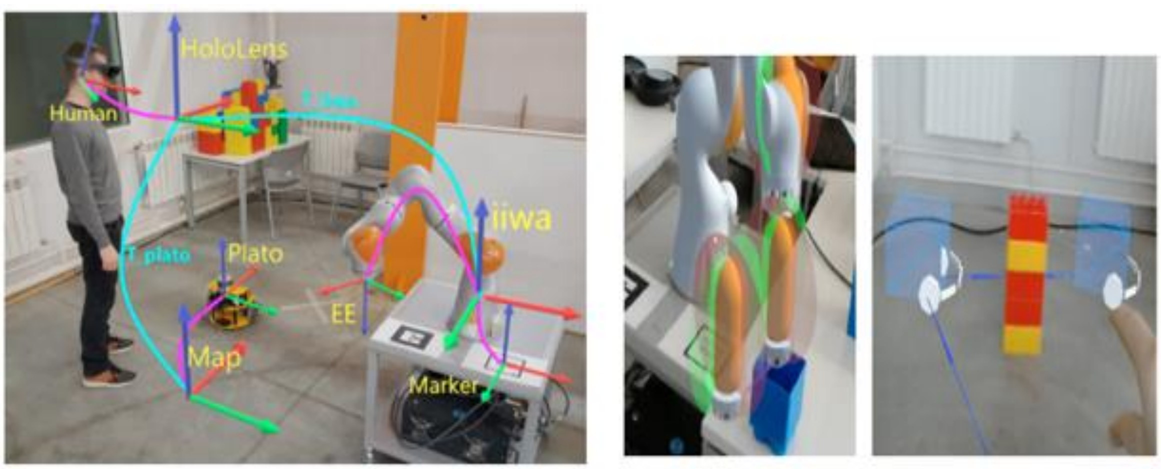


Figure 2-5 Robot control using MR system [47]

In Figure 2-6 AR based fitness program specialists created and executed the program, while participants exercised by viewing the pre-established program on a monitor, monitoring their

posture and accuracy. Participants improved muscular strength, joint range of motion, exercise speed, and exercise control.

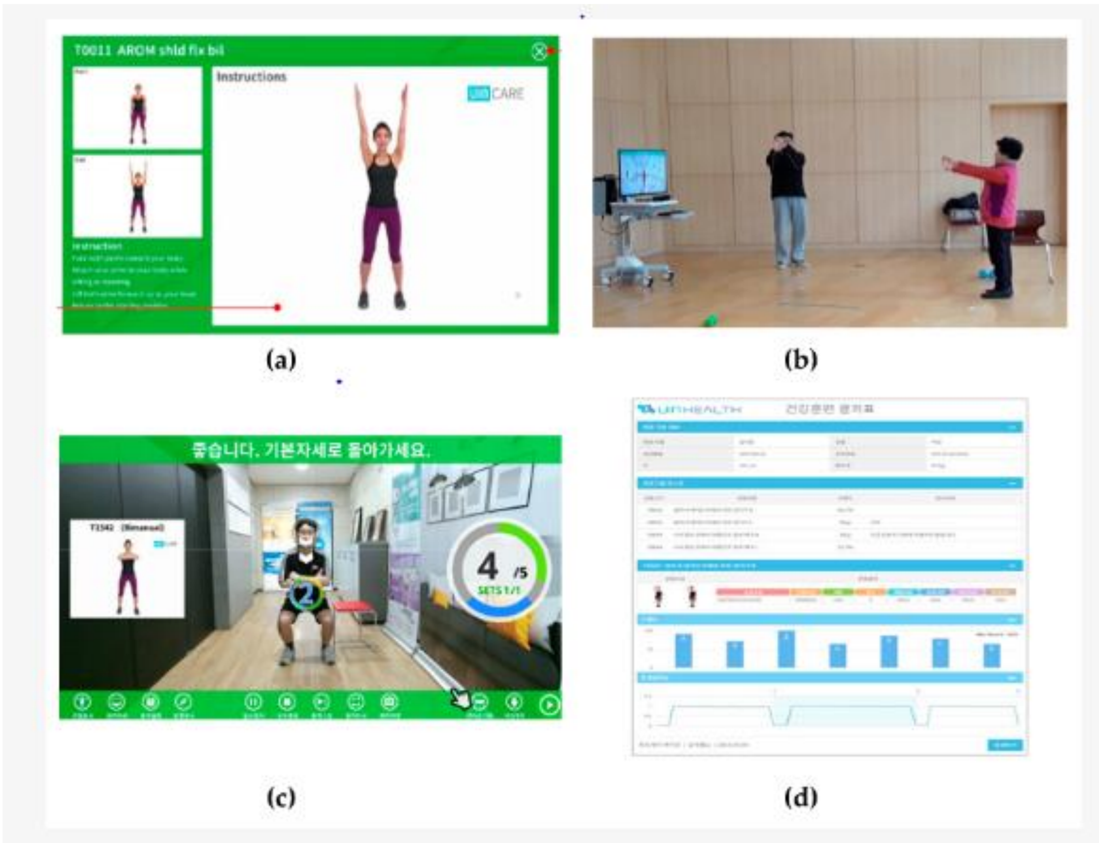


Figure 2-6 AR-based exercise in UIN-HEALTH. (a) Exercise command from a specialist, (b) execution during exercise, (c) monitoring exercise situation, and (d) results of exercise [60]

Users are generally pleased with their experiences while using MR equipment, and their reactions to applications that make use of the technology are highly positive [62]. Researchers often attribute the favorable responses to these programs in their present non-rehabilitation uses to the fact that users are excited to discover the capabilities of MR systems they have never used before [63], [64]. This sense of accomplishment may encourage users to continue with otherwise repetitive rehabilitation routines. People may become tired of reaching for balls to strengthen their motor abilities, but they may like reaching for digital balls presented on a head-mounted display.

MRR programs intended for specific goals, such as rehabilitation, are more successful than MR programs established for general reasons (e.g., entertainment). It's likely that the integration of gaming components into any MR application is the software aspect that gets the most attention [38-39]. It's possible that a standard rehabilitation program may make the patient lose interest, which will slow down their progress toward regaining their physical abilities. On the other hand, incorporating components of games can boost enthusiasm during the rehabilitation process, allowing the user to remain involved and continue working on enhancing their capabilities. There are several constant aspects of MRR programs that have the potential to improve user motivation. The provision of fast feedback is considered to be among the most significant. As a result of the requirement that MRR programs have some form of image recognition in order to blend reality and virtuality, connected software is often able to track the location and movement of users [65], [66]. Program developers often include MRR programs' feedback by using this feature. This feedback ensures that users' motions are noticed, the movements are compared to appropriate rehabilitation activities, and feedback for improvement is provided [67], [68]. This functionality guarantees that users are completing motions correctly, which can both contribute to the improvement of users' physical capabilities and decrease the chances of users suffering injuries.

Finally, MRR applications frequently give automated guidance to users based on movement recognition, allowing users to execute rehabilitative exercises at home [69]. This capacity makes rehabilitation more accessible since users do not need to commute to conduct rehabilitation activities. As a result, MRR programs allow consumers more flexibility over their rehabilitation activities.

CHAPTER 3

ROBOT-ASSISTED TELEREHABILITATION

This chapter discusses rehabilitation, telerehabilitation, neurorehabilitation techniques, robot-assisted rehabilitation, and robot-assisted telerehabilitation.

3.1 Rehabilitation

Rehabilitation is a treatment that can help a patient to regain, maintain, or enhance the abilities necessary for daily living. Rehabilitation is the process of assisting an individual in achieving the highest possible degree of function, independence, and quality of life. The World Health Organization (WHO) [70] defines rehabilitation as "a mix of therapies intended to improve functioning and decrease disability in people with health conditions as they interact with their environment."

3.2 Telerehabilitation

Telerehabilitation is the process of delivering rehabilitation through the use of telecommunication and over the Internet. Remote rehabilitation is now possible to improve technology such as video-calling apps (Microsoft teams, zoom, skype), phone calls, webcams, and screen sharing. This method also enables patients to talk to providers remotely [71] and can be used both to evaluate patients and give them treatment. Telerehabilitation is widely employed in the fields of occupational therapy, psychology, audiology, speech-language rehabilitation, and physical therapy.

3.3 Different Types of Rehabilitation

There are three main types of rehabilitation treatment: occupational therapy, physical therapy, and speech therapy. Each type of rehabilitation helps a person get better in a different way, but the goal is always to get the person back to a healthy, active life. Rehabilitation therapy can help with a wide range of illnesses and injuries. Orthopedic and musculoskeletal injuries like sprains, strains, tears, or post-surgical rehabilitation; neurological injuries like stroke, brain damage, or spinal cord injury; and accident-related multi-trauma injuries are frequently treated.

Occupational therapists (OTs) help people who need special help to do everyday tasks by giving them treatments. OT assist people by making modifications to the items that make it difficult for them to do tasks, including eating, dressing, brushing their teeth, and working. The goal of occupational therapy is to help people do the things they want and need to do so they can live a full and independent life.

Physical therapists help people who are in pain or can't work, move or live a normal life because of their injuries. Physical therapy is usually used to relieve pain, improve movement, help people recover from a stroke, injury, or surgery, help with the recovery of sports injuries, teach people how to use devices like walkers and canes, and deal with long-term illnesses such as heart disease or arthritis.

Speech therapists help persons with speaking problems. Speech therapy treats language, communication, voice, swallowing, and fluency issues. A speech therapist may assist neonates with problems such as cerebral palsy, cleft palate, or Down syndrome that cause difficulty drinking, swallowing, or talking. The purpose of speech therapy is to integrate the mechanics of

speaking with the use of language. As a result, the patient will be able to communicate in more helpful and functional ways.

3.4 Principles of Neurorehabilitation

Maier et al. [74] outlined principles of neurorehabilitation after stroke based on motor learning and brain plasticity mechanisms as follows:

i. **Massed practice/repetitive practice:**

   Massed practice is made up of work episodes in which individuals repeatedly perform a task. Several animal studies have revealed that repetitive motor activity can cause significant changes in the brain area responsible for motor planning. There is evidence that the duration or number of sessions influences repeated practice. Repetitions should be monitored during sessions or treatments to determine the effects of massed practice [74].

ii. **Spaced Practice**

   Spaced practice, also called dispersed practice, is based on the idea that work sessions must include breaks. It is still not clear how the practice of spreading out works. Several studies suggest that breaking up the training process into smaller sessions might help people do better on the final exam. A higher level of dosage or therapy hours can result in a higher speed of recovery.

iii. **Dosage**

   The total number of hours spent in therapy, the duration of a training session, the frequency of training sessions, or the quantity of practice required to enhance learning are all examples of dosage in rehabilitation. According to some data, increasing the number of therapy hours might assist in speeding up the healing process. However, several studies

found that increasing the dose early after a stroke had little benefit. As a result, the precise dose-response relationship must still be identified.

iv. Specific Practice

According to this theory, training or practice under specific conditions leads to improvement in those areas. Training exercises that imitate common activities, such as eating or opening doors, can improve an individual's performance on those tasks in real life. As a consequence, patients' independent activities of daily living (ADL) performance can be significantly improved by focusing on ADL performance throughout therapy [74].

v. Goal-Oriented Practice

The goal-oriented practice focuses not only on movement patterns but also on couplings that make it easier to reach the goal [75]. In general, paying more attention to what will happen when you move can help you improve your motor skills. When the same workouts are done with or without a goal, activities with a goal lead to better results.

vi. Variable Practice

There are two different approaches to variable practice: the first is the variability of practice, and the second is random practice. Both strategies have a good deal of success regarding untrained tasks or motions. According to studies that used functional magnetic resonance imaging (fMRI) and transcranial magnetic stimulation (TMS), variable practice improved neuronal activity. This was especially true in areas of the brain responsible for motor learning. The effectiveness of variable practice may have something to do with neuromodulatory systems like the dopaminergic system, which work to maintain brain plasticity [76].

vii. Increasing Difficulty

Many issues or tasks that investigate motor learning are often connected with task complexity. The need for training and other factors associated with the work, as well as how challenging the activity is in comparison to an individual's talent, may readily define task difficulty. More practice can help to reduce prediction mistakes. If people can handle the difficulty of the task, their motor skills will be much better. But if the level of difficulty is too high for a person to handle, it could hurt their overall performance [77].

viii. Multisensory Stimulation

Significant cognitive capacities include sensorimotor control and the perception of various sensations. One neuron could be responsible for several types of sensory input, according to the findings of a study that was carried out on a cat. Patients recovering from visual, unimodal, or auditory deficiencies might benefit from these several parts of training [78].

ix. Rhythmic Cueing

The study of the temporal relationship between body movement and rhythmic stimulus created by the surrounding environment is referred to as neuroentrainment. Visual, auditory, and vestibular stimuli are examples of sensory modalities that may be used for entrainment. Internal rhythmic movement is mainly controlled by auditory-motor synchrony. As a result, auditory signals are critical in coordinating movements to rhythmic patterns. The research found neural connections between the auditory and motor systems. Several meta-analyses have discovered that rhythmic cueing improves upper-limb dysfunctions, particularly after stroke [79].

x. Explicit Feedback/Knowledge of Results

Explicit feedback is defined as input concerning specific goals that might be vocal, terminal, or enhanced. This feedback can be more powerful than extrinsic rewards [23].

This sort of input is delivered by explicit feedback and is based on cognitive processing. It is based on quantitative or qualitative process outcomes, such as success or failure. A study was conducted to analyze different feedback types; it was reported that explicit feedback has positive effects on motor function [80].

xi. Implicit Feedback/Knowledge of Performance

The implicit feedback concept of motor rehabilitation involves giving the patient performance-based feedback during exercise without referring to a specific goal or outcome. This feedback helps patients correct sensorimotor prediction mistakes, leading to implicit learning. New technology allows online implicit feedback [81].

xii. Modulate Effector Selection

Following a stroke, severe pain and weakness frequently limit the use of the afflicted limb. As a result, the injured limb that isn't utilized enough may lose neural activity. The most effective and widely used therapeutic strategy to address this problem is constraint-induced movement therapy (CIMT). According to fMRI research, the CIMT program is useful in boosting the strength and utilization of the afflicted limb [74].

xiii. Action Observation/Embodied Practice

A research study found that those who completed a particular activity after seeing the performance of others performed better. According to a meta-analysis, the human parietal and promotor regions are in charge of movement execution. As a result of its brain activation qualities, action observation can be beneficial for stroke victims [74].

xiv. Mental Practice/Motor Imagery

The process of motor imagery and mental practice is one in which a person imagines a psychological rehearsal of future motions in order to improve their performance. The use of

motor imagery has been shown to have beneficial benefits on learning as well as therapeutic effectiveness; nevertheless, the physical practice has shown to have more desirable consequences on learning. Patients undergoing stroke therapy may also benefit from using motor imagery. The beneficial findings for mental practice were also validated by a meta-analysis [74].

xv. Social interaction:

Social interaction in motor rehabilitation refers to the improvement of a patient's performance based on the feedback they receive from their social interactions with others. If a person's social dependence or acceptability is affected by their motor skill performance for ADL-specific activities, this can positively impact their learning performance during exercises based on feedback from others [82].

3.5 Robot-Assisted Upper Limb Rehabilitation

A variety of upper-limb rehabilitation exercises, including passive, active-assist, resistive, and active exercises, should be included in the program of robot-assisted therapy. These therapies should also include the activities that are detailed in sections 3. During passive rehabilitation exercises, the patient is not expected to actively participate in any exercises/training. During this activity, the patient is provided with assisted mobility or directed movement from an external source, such as a physical therapist or a rehab device designed for rehabilitation. Patients' range of motion (ROM) should improve as a result of this activity. In the passive rehabilitation mode, the rehabilitation device will move the patient's arm in 2D and 3D space. This is mainly done to decrease spasticity and promote the range of motion. Activities that fall under the category of active-assistive rehabilitation are ones in which the patient actively puts their muscles to work to complete a task. For illustration's sake, the person being studied may be tasked with drawing a

straight line. The patient will receive assistance from the rehabilitation equipment if they cannot complete the task. The development of greater muscular strength is the goal of this activity. Resistive rehabilitation exercises require the patient to actively engage in the use of their muscles in order to accomplish a goal. For illustration's sake, the subject can be instructed to draw a square box on a sheet of paper or computer screen. Because of this circumstance, the rehabilitation tool will provide a modest amount of motion resistance, making it difficult for the patient to complete the task. The development of greater muscular strength is the goal of this activity.

In this research, we developed an end-effector-type rehabilitation robot, named DMRbot, intending to deliver various types of rehabilitation therapy. We have also developed a telemanipulation framework telerehabilitation with the developed robot.

CHAPTER 4

DEVELOPMENT OF DMRbot

This chapter describes the DMRbot's design, workspace, capabilities, kinematics, and control.

4.1 Design of DMRbot

In design goals were established with a focus on the principles of motor rehabilitation. Next, the design specifications were finalized, and a CAD model of the robot was done. After that, the robot parts are fabricated with traditional machining and rapid manufacturing processes. Finally, the robot was integrated with the mechatronic system available at the UWM BioRobotics Lab with necessary modifications in the programming to maneuver the DMRbot in a specific position in 2D and 3D space representing a passive rehab exercise motion.

4.2 Design goals

To make the DMRbot a minimum viable product to provide a robot-aided telerehabilitation therapy, a set of design constraints was set, including limiting the robot to only 3 degrees of freedom (DoFs). The design objectives selected are listed below:

i. DoFs: 3

ii. Workspace: The robot workspace should cover the human upper limb workspace.

iii. Ambidextrous operation: The robot should allow ambidextrous operation, left-handed and right-handed exercises in the same configuration.

iv. Joint torque requirement: Higher torque capacity motor and gear reducers to reduce physical joint torque limitations

v. Weight: Thicker and lightweight links should be fabricated with carbon fiber tubing to ensure light weight and the minimum viable product (MVP) prototype for upper limb rehabilitation.

4.3 Design Specifications and Component Selection

The following components and component specifications were finalized based on the above design goals.

a. **Materials:** A combination of carbon fiber rectangular tubing and Aluminum 6061 alloy is used for structural components, and 3D printable rapid prototyping plastic is used for covering and mounting parts.
b. **Actuators:** Brushless DC motors (from the Maxon group) were combined with harmonic drive gear reducer units to make the joint actuators. For Joint-1 Maxon EC90 Series 90-watt motor was selected, and for Joint-2 and Joint-3 Maxon EC45 Series 70-watt motors were selected. Detailed datasheets of these motors are provided in Appendix-A of this document. The harmonic Drive CSF-series compact gear units with 100:1 reduction ratio, “CSF-17-100-2UH” was selected to reduce the motor speed and increase the torque of the motors. CSF-series harmonic drive gear reducer units combine the reducer with an output “cross roller” bearing, allowing the gear reducer unit to be used as a complete robot joint directly. Appendix-A shows the technical specification and bearing loading details of the CSF-17-100-2UH gear unit.
c. **Drivers and communication protocol:** The central computer unit serves to execute the control algorithm of the DMRbot. Three dedicated motor drivers (EPOS4 COMPACT 50/5 and EPOS4 COMPACT 50/8) are used to control the motor. The devices are powered from a 350 W power source at 24 V needs. The EPOS range of digital position controllers for

Brushed and Brushless DC (BLDC) motors from the Maxon group is popular in industrial and robotics applications. The EPOS4 series provides an option for using CANopen, a higher layer protocol, and device profile specifications based on Controller Area Network (CAN) bus for communication with a master controller. CANopen protocol uses two modes of communication, Service Data Objects (SDO) and Process Data Objects (PDO). SDO communication is used to configure and operate EPOS4 devices in the network in a point-to-point manner over the CANbus. This communication cannot be used for real-time motion control applications, and is not suitable for synchronous control of multi-motor systems over the same bus. On the other hand, PDO communication allows real time data manipulation and synchronization of objects [83].

Design specifications of components of the developed DMRbot are summarized in Table 4.1

Table 4.1 Design specifications and selected components for DMRbot at a glance

Fabrication		
Material	Carbon Fiber Rectangular Tubing (25505 - Tube - Rectangle - Fabric - Thin Wall - 1.00 x 2.00 - 1.10 x 2.06)	
Fabrication process	CNC machining and FDM 3D printing	
Actuators		
Location	Joint-1	Joint-2 & Joint-3
Motors	Maxon EC45 90 watt	Maxon EC45 70 watt
Operating voltage (V)	24v	24v

Motor Nominal Speed (rpm)	2590	4860
Nominal Current (A)	6.06	3.21
Torque Constant (mNm/A)	70.5	36.9
Nominal Motor Torque (mNm)	444	128
Weight (g)	600	141
Motor drivers	EPOS4 COMPACT 50/8 CAN	EPOS4 COMPACT 50/5 CAN
Motor driver current rating (A)	30 (peak) 8 (continuous)	15 (peak) 5 (continuous)
Motor driver input	Hall sensor signals, encoder signals, analog and digital inputs, sensor signals, functionality of analog & digital outputs	Hall sensor signals, encoder signals, analog and digital inputs, sensor signals, functionality of analog & digital outputs
Motor driver feedback	Analog and digital outputs, functionality of analog & digital outputs	Analog and digital outputs, functionality of analog & digital outputs
Gear reducer	Harmonic Drive CSF-17-100-2UH	Harmonic Drive CSF-17-100-2UH
Ratio	100:1	100:1
Gear reducer average output torque limit (Nm)	39	39
Communication & Interface	CANopen & Gateway function USB-to-CAN	

4.4 CAD Model and Mechanical Design

The proposed DMRbot was designed based on a human reachable workspace to provide UL rehab therapy in the full range of UL workspace. To make the DMRbot a minimum viable product to provide robot-aided rehabilitation therapy, a set of CAD models for all the components were designed in SolidWorks software is shown in Figure 4-1. This CAD model was used to analyze mass and inertia properties and assembly features, clearances, and required dimensions for each joint and link. The CAD model's output was directly used to generate CNC toolpaths, 3D printing codes for fabrication and carbon fiber rectangular tubing.

Figure 4-1: CAD model of DMRbot

This DMRbot mainly consists of a base and three links (link-1, link-2, and link-3); the base and one for each link are illustrated and described as follows:

Base:

The robot's base is comprised of a 20x20 aluminum profile. It houses Joint-1's motor (Motor-1). The Joint-1 consists of the harmonic drive gear reducer mounted directly to the top base part, with the motor mounted on its back with a custom-designed motor adapter. Figure 4-2 shows the base assembly with an exploded view of the base.

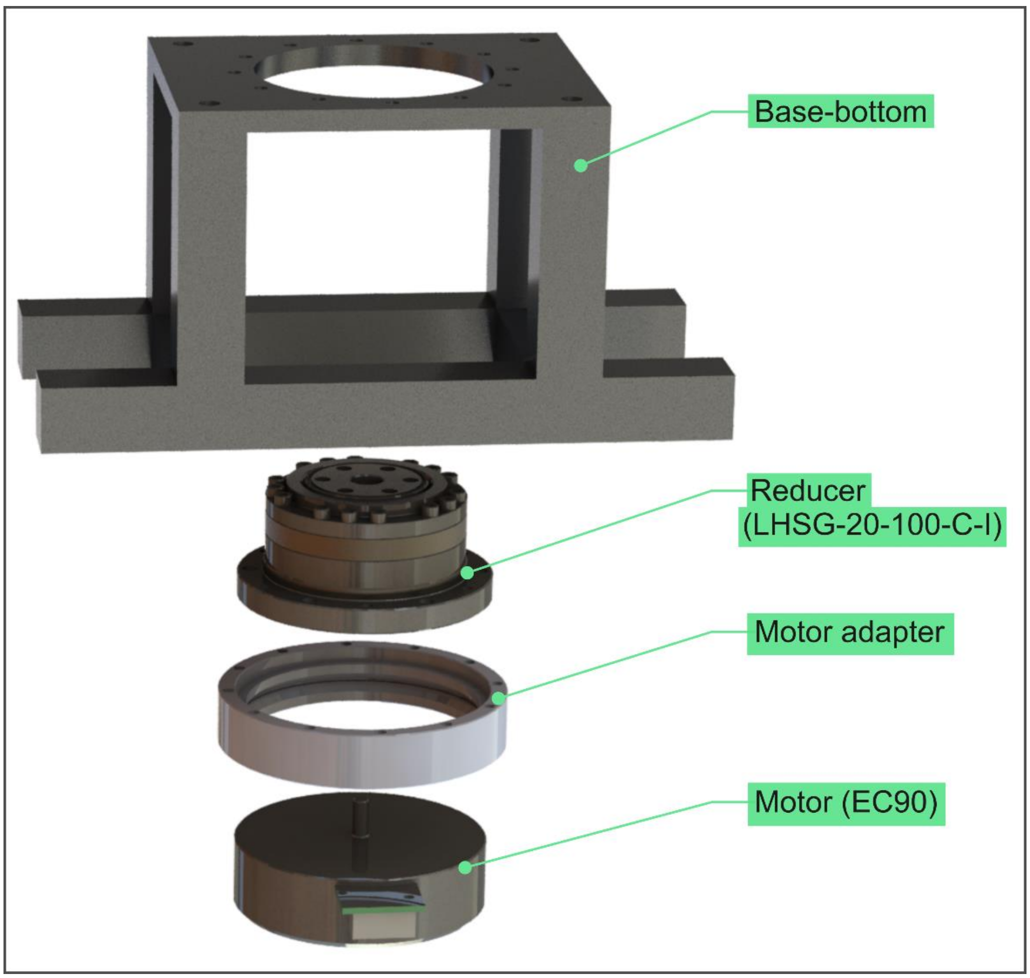


Figure 4-2: Base assembly exploded view

Link-1:

Figure 4-3 depicts the Link-1 assembly with the Joint-1 exploded. This arrangement consists of a manufactured aluminum part with a harmonic drive gear reducer mounted directly to it. A motor adapter plate attaches the motor to the harmonic drive.

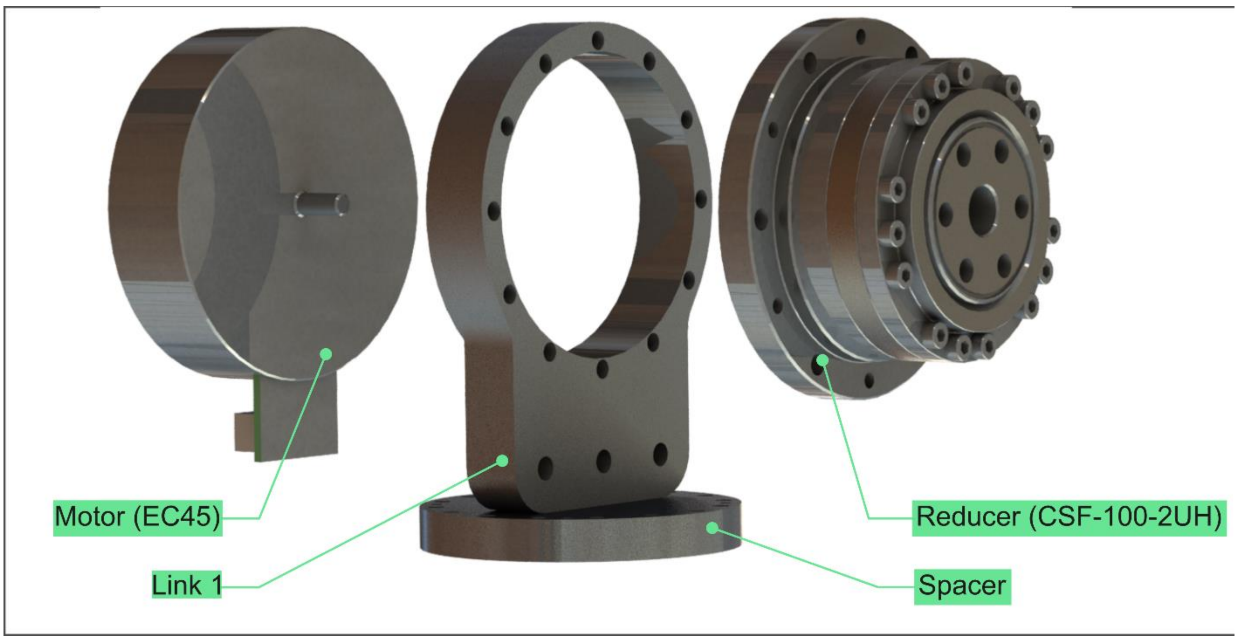


Figure 4-3: Link-1 assembly exploded view of Joint-1

Link-2:

Figure 4-4 depicts the Link-2 assembly. This assembly's carbon fiber and aluminum parts are directly attached to the end part of link-2 through a harmonic drive gear reducer. The Joint-2 (Motor-2) is an assembly between the link-1 and link-2, and is located at Maxon motor-2.

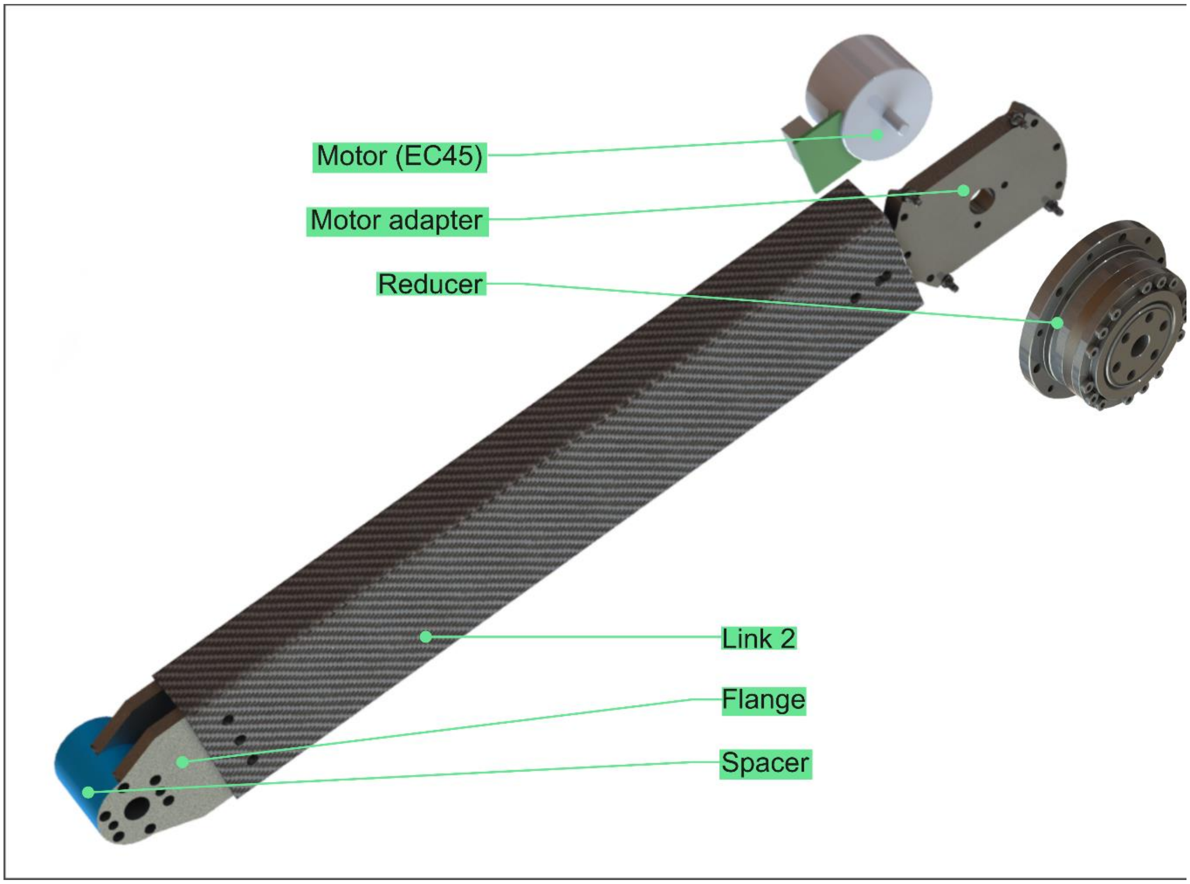


Figure 4-4: Link 2 assembly exploded view

Link-3:

Joint-3 is an assembly of link-2 and link-3, and is located at Maxon motor-3. In this assembly, the carbon fiber and aluminum parts combine with a link-3. The end of the link contains the end-effector, consisting of the force sensor and the handle. The handle is a standard horizontal cylinder; the handle has a base part that mounts on the force sensor, 3D printed in polycarbonate plastic.

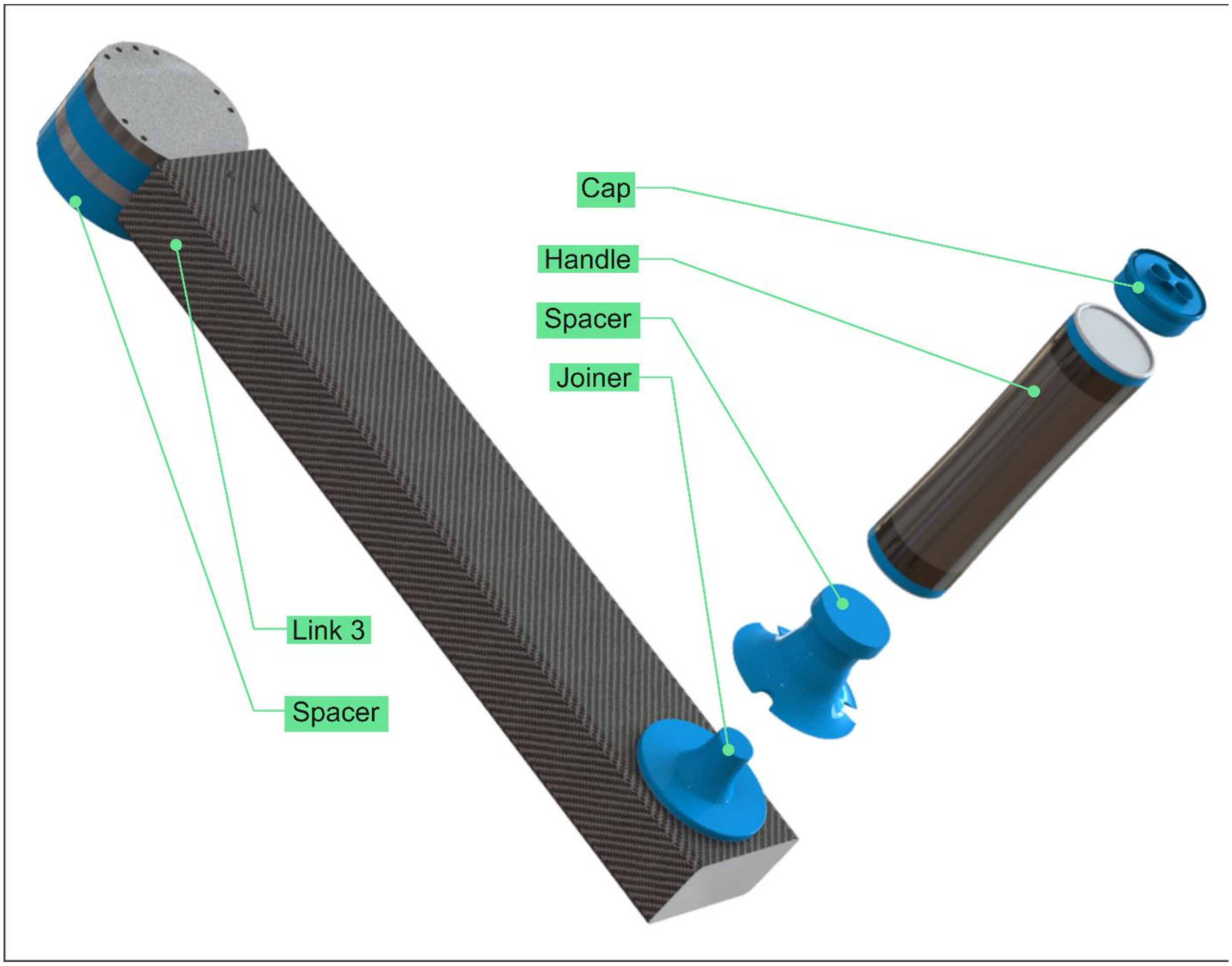


Figure 4-5: Link 3 assembly exploded view of End-effector (Bottom)

4.5 Kinematic Modeling of DMRbot

The position and orientation of the DMRbot end-effector relative to the joint angles are obtained from the forward kinematics of the robot. For the forward kinematics analysis of the DMRbot, modified Denavit-Hartenberg (DH) [84] parameters are used. To describe the location of each robot link relative to its neighbors, a coordinate frame (link frame) is attached to each link of the robot.

4.5.1 Forward Kinematics

The goal of the forward kinematics is to compute the end-effector position as a function of joint angles. To do this, we first attach reference frames for each link in the DMRbot. Figure 4-6 presents a front view of the DMRbot with link-specific reference frames. The intersections between the dotted black lines represent the actual origin positions of the respective reference frames.

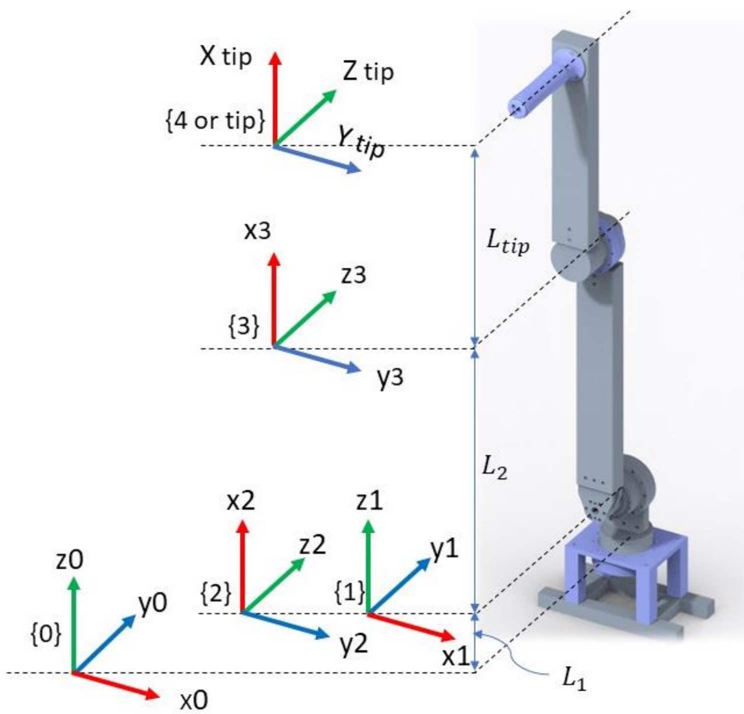


Figure 4-6: Coordinate frame assignment for 3DoF DMRbot

To obtain the DH parameters, it is assumed that the coordinate frames (i.e., the link-frames that map the axis of rotation of one frame to the successive) coincide with the corresponding joint axes of rotation, i.e., frame {1} coincides with joint 1, frame {2} with joint 2, frame {3} coincide with joint 3 and finally, frame {4 or tip} define the end-effector position of the DMRbot. The frame

{0} defines the base frame (world frame) of the robot. The DH parameters corresponding to the link-frame assignment in Figure 4-6 are summarized in Table 4.2.

Table 4.2 Modified Denavit-Hartenberg parameters

Joint *(i)*	$\boldsymbol{\alpha_{i-1}}$	$\boldsymbol{a_{i-1}}$	$\boldsymbol{d_i}$	$\theta_{\boldsymbol{i}}$	**Variable**
1	0	0	L_1	$\theta_{\mathbf{1}}$	θ_1
2	-90	0	0	$\theta_{\mathbf{2}}$	$\theta_2' = \theta_2 - \pi/2;\ \theta_2'' = \theta_2' - \pi$
3	0	L_2	0	$\theta_{\mathbf{3}}$	$\theta_{\mathbf{3}}$
4 or Tip	0	L_{tip}	0	0	None

Where, αi-1 is the link twist, ai-1 corresponds to link length, di stands for link offset, and θi is the joint angle of the DMRbot.

The general form of a link transformation that relates frame {i} relative to the frame {i-1} is:

$$ {}^{i-1}_{i}T = \begin{bmatrix} {}^{i-1}_{i}R^{3\times3} & {}^{i-1}_{i}P^{3\times1} \\ 0^{1\times3} & 1 \end{bmatrix} \tag{4.1} $$

Where, ${}^{i-1}_{i}R$ is the rotation matrix that represents the frame $\{i\}$ relative to frame $\{i-1\}$ and can be articulated as follows:

$$ {}^{i-1}_{i}R = \begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 \\ \sin\theta_i \cos\alpha_{i-1} & \cos\theta_i \cos\alpha_{i-1} & -\sin\alpha_{i-1} \\ \sin\theta_i \sin\alpha_{i-1} & \cos\theta_i \sin\alpha_{i-1} & \cos\alpha_{i-1} \end{bmatrix} \tag{4.2} $$

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

$$ {}^{i-1}_{i}P = [a_{i-1} \quad -sin(\alpha_{i-1})d_i \quad cos(\alpha_{i-1})d_i]^T \tag{4.3} $$

Using equations (4.1)-(4.3) the individual homogeneous transfer matrix that relates two successive frames of the DMRbot can be found as equation (4.4-4.7):

$$ {}^{0}_{1}T = \begin{bmatrix} \cos\theta_1 & -\sin\theta_1 & 0 & 0 \\ \sin\theta_1 & \cos\theta_1 & 0 & 0 \\ 0 & 0 & 1 & L_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4.4} $$

$$ {}^{1}_{2}T = \begin{bmatrix} \sin\theta_2 & \cos\theta_2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ \cos\theta_2 & -1.0\sin\theta_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4.5} $$

$$ {}^{2}_{3}T = \begin{bmatrix} \cos\theta_3 & -\sin\theta_3 & 0 & L_2 \\ \sin\theta_3 & \cos\theta_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4.6} $$

$$ {}^{3}_{tip}T = \begin{bmatrix} 1 & 0 & 0 & L_{tip} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4.7} $$

The homogenous transformation matrix that relates frame $\{4\ or\ Tip\}$ to frame $\{0\}$ can be obtained by multiplying individual transformation matrices that result in the generic form of equation (4.8). And the position of the tip with respect to the base frame can be found using equation (4.9).

$$ {}^{0}_{tip}T = \begin{bmatrix} sin(\theta_2+\theta_3)\, cos\,\theta_3 & cos(\theta_2+\theta_3)\cos\theta_1 & -\sin\theta_1 & \sigma_1\cos\theta_1 \\ sin(\theta_2+\theta_3)\, sin\,\theta_1 & cos(\theta_2+\theta_3)\sin\theta_1 & \cos\theta_1 & \sigma_1\sin\theta_1 \\ cos(\theta_2+\theta_3) & -\,sin(\theta_2+\theta_3) & 0 & \sigma_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4.8} $$

$$ where, \sigma_1 = L_{tip} sin(\theta_2+\theta_3) + L_2 sin(\theta_2),\ \ \sigma_2 = L_1 + L_{tip}\, cos(\theta_2+\theta_3) + L_2\, cos(\theta_2) $$

$$ {}^{0}_{tip}p = \begin{bmatrix} P_x \\ P_Y \\ P_Z \end{bmatrix} = \begin{bmatrix} \cos\theta_1 \left(L_{tip}\sin(\theta_2+\theta_3) + L_2\sin\theta_2\right) \\ \sin\theta_1 \left(L_{tip}\ \sin(\theta_2+\theta_3) + L_2\sin\theta_2\right) \\ L_1 + L_{tip}\ \cos(\theta_2+\theta_3) + L_2\cos\theta_2 \end{bmatrix} \tag{4.9} $$

4.5.2 Inverse Kinematics

The previous section has shown how to determine the end-effector position given the robot's joint angles. A problem of practical interest in the inverse kinematics problem is to find the joint angles given the desired position and orientation of the end-effector with respect to the base frame. In this research, we have used the geometric approach to solve the inverse kinematics of DMRbot.

4.5.3 Geometric inverse kinematic solution

In a geometric approach to finding an inverse kinematic solution, the robot spatial geometry is decomposed into several plane-geometry problems. As the DMRbot is a 3DoFs planar robot, plane geometry, as shown in Figure 4-7 can be applied directly to find a solution.

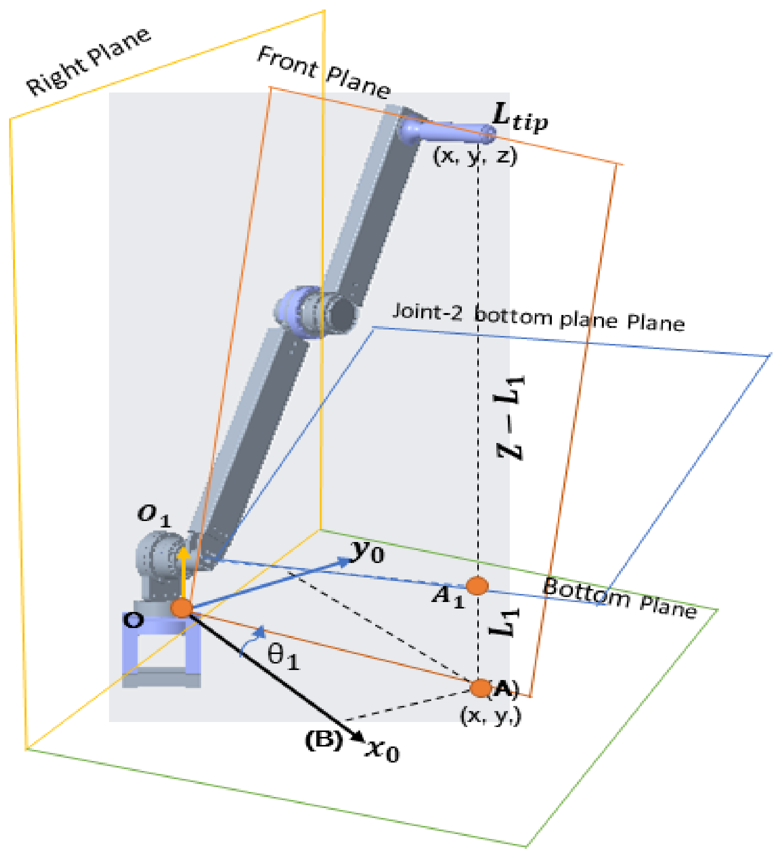


Figure 4-7: Inverse kinematics model of the 3DoF DMRbot

Making a projection of tip location on bottom plane (point A as shown in Figure 4-7), we obtain a triangle ▲OAB. From ▲OAB,

$$tan\theta_1 = \left(\frac{y}{x}\right) \tag{4.10}$$

$$\Rightarrow \theta_1 = \arctan\left(\frac{y}{x}\right) \tag{4.11}$$

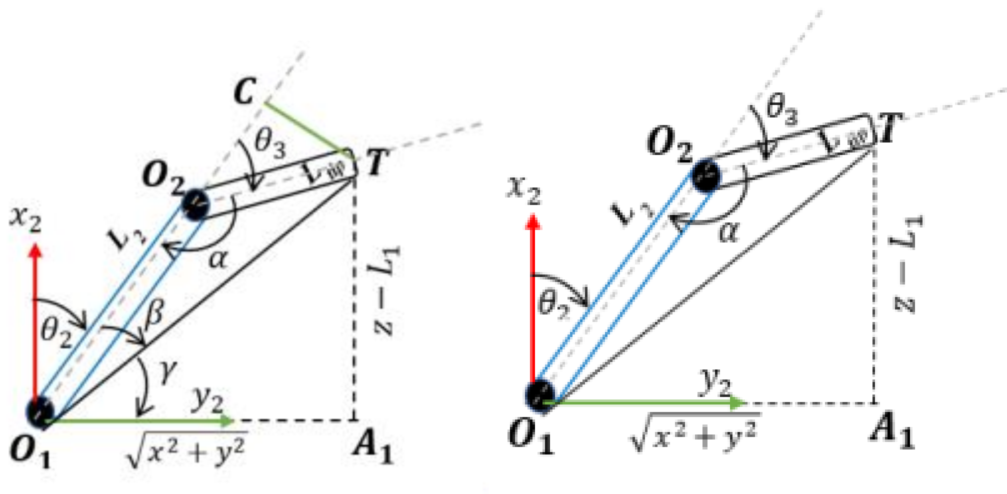


Figure 4-8: Geometric inverse kinematics model of DMRbot

Here, O_1A_1 = OA = $\sqrt{x^2 + y^2}$ (4.12)

From $\blacktriangle O_1A_1T$,

$(O_1T)^2 = (O_1A_1)^2 + (A_1T)^2$

⇨ $(O_1T)^2 = (x^2 + y^2) + (z - L_1)^2$

(4.13)

Using the cosine rule, from the triangle $\blacktriangle O_1O_2T$,

$(O_1T)^2 = (O_1O_2)^2 + (O_2T)^2 - 2\,(O_1O_2)\,(O_1T)\,cos\,\alpha$

⇨ $(x^2 + y^2) + (z - L_1)^2 = {L_2}^2 + {L_{tip}}^2 - 2\,L_2L_{tip}\cos\,(180 - \theta_3)$

(4.14)

⇨ Here, $\cos\,(180 - \theta_3) = -\cos\,\theta_3$

⇨ $\cos\,\theta_3 = \frac{(x^2+y^2) + (z - L_1)^2 - {L_2}^2 + {L_{tip}}^2}{2\,L_2L_{tip}}$

$$\Rightarrow \theta_3 = \cos^{-1}\left(\frac{(x^2+y^2) + (z - L_1)^2 - L_2{}^2 + L_{tip}{}^2}{2\, L_2 L_{tip}}\right) \quad (4.15)$$

From Fig 4.9 we can get,

CT = $L_{tip} sin\ \theta_3$;

$O_2C = L_{tip} sin\ \theta_3$

$$\tan \beta = \frac{CT}{O_1C} = \frac{L_{tip} sin\ \theta_3}{L_2 + L_{tip} cos\ \theta_3}$$

$$\Rightarrow \beta = \arctan\left(\frac{L_{tip} sin\ \theta_3}{L_2 + L_{tip} cos\ \theta_3}\right) \quad (4.16)$$

From ▲O_1A_1T,

$$\tan \gamma = \frac{CT}{O_1C} = \left(\frac{z - L_1}{\sqrt{x^2+y^2}}\right)$$

$$\Rightarrow \gamma = \arctan\left(\frac{z - L_1}{\sqrt{x^2+y^2}}\right) \quad 4.17$$

$$\theta_2 = 90 - \gamma - \beta = 90 - \arctan\left(\frac{z - L_1}{\sqrt{x^2+y^2}}\right) - \arctan\left(\frac{L_{tip} \sin\theta_3}{L_2 + L_{tip} \cos\theta_3}\right) \tag{4.18}$$

4.6 Control of DMRbot

Two different kinds of control loops are used to implement this control architecture: a position loop and a velocity control loop (see Figure 4-9).

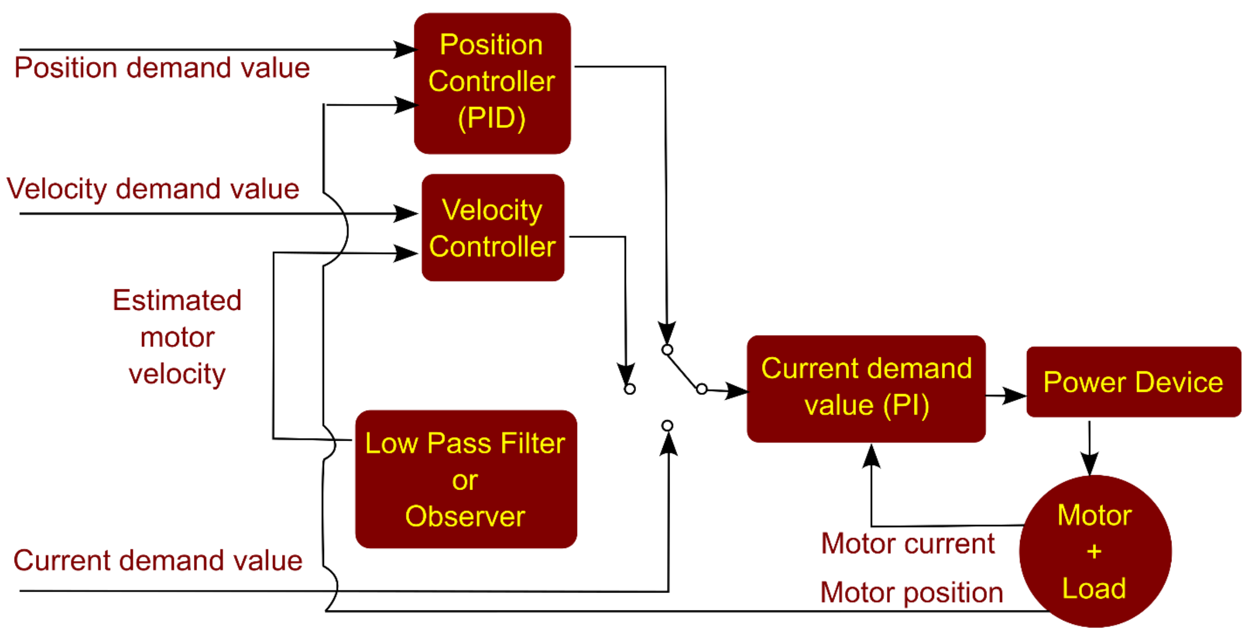


Figure 4-9: Control architecture of the system

A Proportional Integral Derivative (PID) control technique has been used for the initial testing and control of the developed DMRbot [90]**.** The joint torque commands are expressed by equation (4.19):

$$\tau = K_P(\theta_d - \theta) + K_V(\dot{\theta}_d - \dot{\theta}) + K_I \int (\theta_d - \theta)\, dt \tag{4.19}$$

Where,

$\theta_d, \theta \in \mathbb{R}^{3x1}$ are the vectors of desired and measured joint angles,

$\dot{\theta_d}$, $\dot{\theta} \in \mathbb{R}^{3x1}$are the vectors of desired and measured joint velocities,

K_P, K_V, *and* K_I are the diagonal positive definite gain matrices,

$\tau \in \mathbb{R}^{3x1}$ is the generalized torque vector.

E is an error vector, and its derivative $\dot{E}$ given by equations (4.20) and (4.21) respectively:

$$E = \theta_d - \theta \tag{4.20}$$

$$\dot{E} = \dot{\theta_d} - \dot{\theta} \tag{4.21}$$

Therefore, equation (4.19) has been reformulated as an error equation (4.22):

$$\tau = K_P E + K_V \dot{E} + K_I \int E\, dt \tag{4.22}$$

By decoupling relation equation (4.22), the individual torque command for each joint is given by equation (4.23).

$$\tau_i = K_{P_i} e_i + K_{V_i} \dot{e}_i + K_{I_i} \int e_i \, dt \tag{4.23}$$

CHAPTER 5

DIGITAL TWIN OF DMRbot

This chapter presents an overview of digital twins, digital threads, and digital thread features. Following that, the step-by-step method of developing a digital twin with PTC Vuforia Studio and the Unity platform is presented.

5.1 Digital Twin

A digital twin is described as a virtual representation of a real product, task, or fundamental process. A digital model comprises real-time data and therefore is not a true digital twin if it lacks data. Digital twins are customized to each product, process, or job. It is simple to use augmented reality (AR) to bring a digital image of a physical product or job into the real environment for linking clients and servers. A scanning code is required to access the digital twin, which may be available in many formats on a smartphone or any other device that aids in the loading and creation of the whole experience for viewing in AR. In addition, augmented reality may support many digital twin experiences within a single AR session. For example, a single AR experience may include viewing a single piece of data for any product. Another possibility is to do maintenance on that product [99].

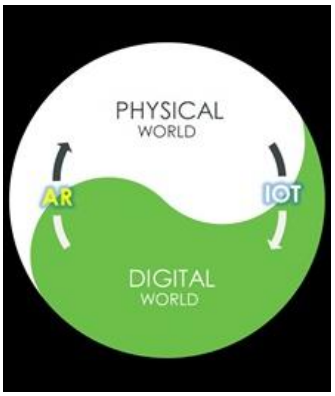


Figure 5-1 Connecting the digital twin and physical world

5.2 Digital Thread

The digital thread is a network of communication that makes it possible to keep real-time data in sync. In addition, it acts as an interface between the real world and the digital world. This expandable set of data that is accessible to the general user allows continuity among objects, processes, and individuals. It can also be thought of as a collection of different pieces of information gathered about a product over time. Digital threads can help find out how customers use certain products and what else they want from them. With the help of digital threads, the company can get information that helps it make its products better. This information can help improve customer compliance and save money at the same time [100].

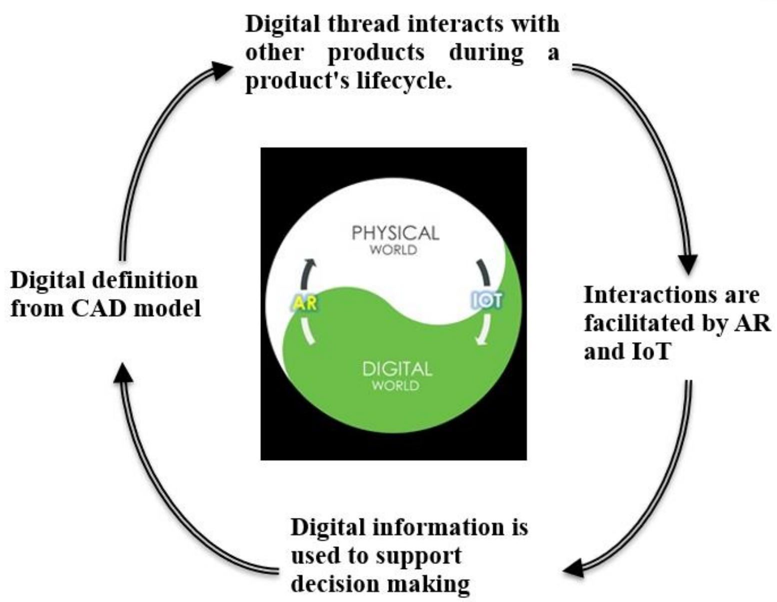


Figure 5-2 Processing flow of digital twin and physical world

IoT data provides lifecycle visibility. The digital thread ensures that all the process components can access the latest sensor data in a product lifecycle (sample see Figure 5-2). It connects design requirements to design execution, manufacturing instructions, supplier management, and end-customer operations. Using historical data to compare to real-time sensor data enhances asset

use. Users can simulate what-if scenarios to make design, operational, and performance choices using models. Real-time sensor data can be analyzed and displayed to convey statistics. Historical and current data comparisons help forecast future trends and improve high-level decision-making.

5.3 Digital Thread Features [100]

In the process of creating a digital twin, the digital thread is also considered an essential component. The digital twin and the digital thread are connected to one another. The digital information collected from the digital thread of a physical entity is used by digital twins to create a digital representation of the information. The data contained inside the digital thread may be accessed through the utilization of a digital twin. [101].

We have highlighted below some [102] of the things that digital twins may enable:

- The digital twin uses digital thread data from an actual product.
- It keeps track of product history which is important for future work and job directions.
- It provides multiple configurations of the same model.
- It makes intelligent design recommendations based on service history.
- Additionally, it offers remote access and maintenance notifications.

We created a digital twin of DMRbot in two different methods so that we could operate two different systems. To begin, we utilized software from PTC Vuforia studio to create a digital twin for both physical and virtual joystick control. The second thing that we did was develop a virtual model in the Unity studio platform and control and display the real movement of the DMRbot.

5.4 PTC Vuforia Studio

PTC Inc [103] created Vuforia Studio, which is considered a web-native tool. This tool is simple to use for a variety of task-specific Experience Services [99]. This platform offers a development

environment for creating industrial 2D/3D augmented reality applications. Vuforia Studio can optimize CAD models, bind those optimized models to IIoT platforms (ThingWorx), and provide AR Studio Experience Services, as shown in *Figure 5-3* (Vuforia Studio architecture and process flow). AR applications can be manufactured for phones, tablets, and Microsoft HoloLens 2 [102]. The Vuforia View app can be used to get to the Studio Experience Service. The studio interface is a drag-and-drop feature that lets people create new apps even if they have never programmed before [96]. Integrating different PTC products allows the transfer of data easily and use of it in many different environments [103]. Using real-time data from the Internet of Things (ThingWorx), Vuforia Studio can also improve the performance of equipment and analyze how it is working [102]. Since Vuforia Studio has all of these benefits, we have decided to use it in this research.

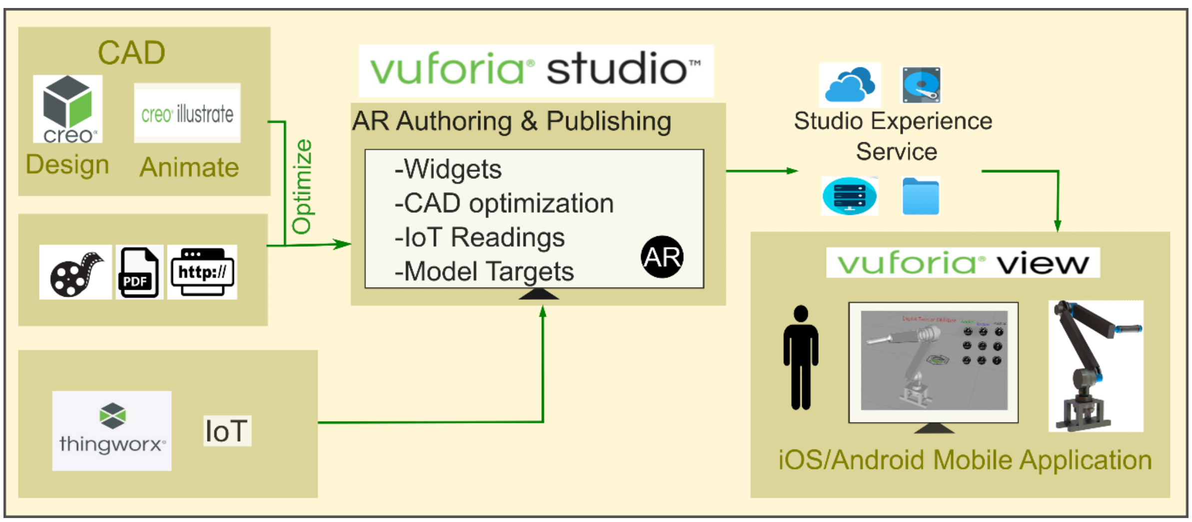


Figure 5-3 Vuforia Studio architecture and process flow [101]

5.5 Digital Twin Development Process

Using PTC Creo, the 3D CAD model of the robot was put together, and PTC Vuforia Studio was used to turn the CAD model into a digital twin. *Figure 5-4* shows how to use Creo and Vuforia Studio to make a digital twin of a robot. The process is broken down into three main steps:

1. Nest the assembly in Creo.
2. Create the model hierarchy in Vuforia Studio.
3. Develop an application for Vuforia Studio.

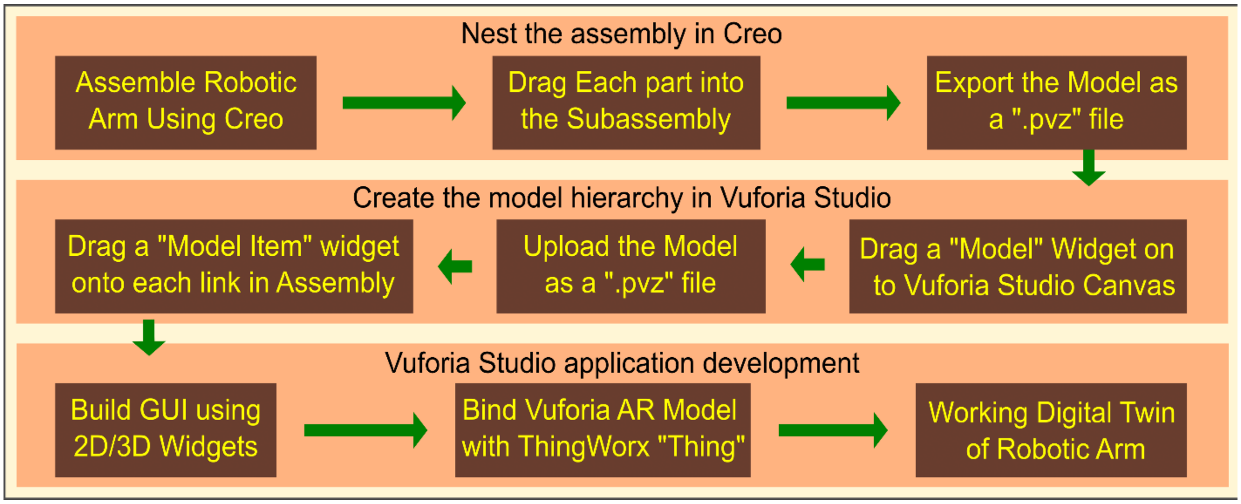
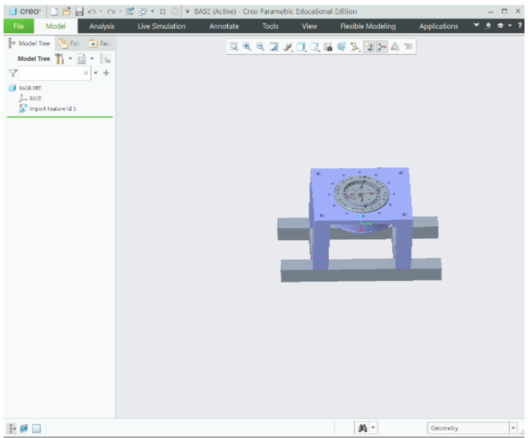


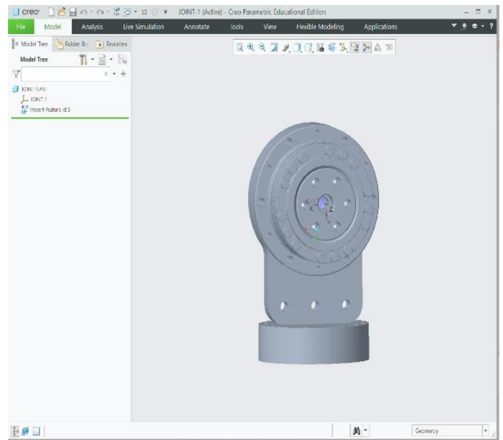
Figure 5-4 Flowchart for building Digital Twin of the robot using Creo and Vuforia Studio

5.5.1 Nest the Assembly in Creo

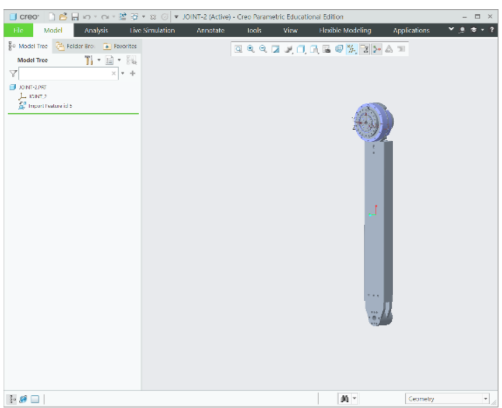
The development of a digital twin began with the assembling of the DMRbot's base to link-3. PTC Creo is used to assemble all of the robot joints (CAD modeling software). Individual robot joints are represented in Figure 5-5, and the entire robot is depicted in Fig. 5.4. Figure 5-6 depicts how to make subassemblies for each joint. Each joint is dragged into the subassembly under the hierarchy, as shown in Figure 5-7, and the model is ready to export for Vuforia Studio as a ". pvz" file.



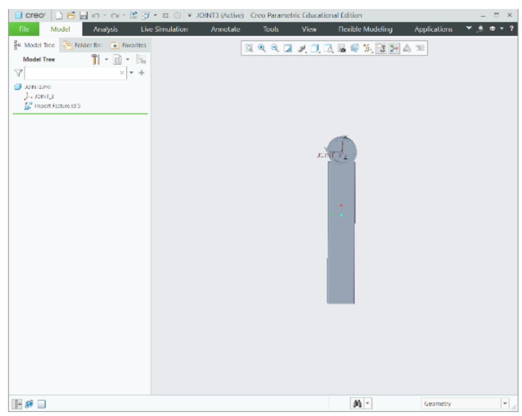
(a)



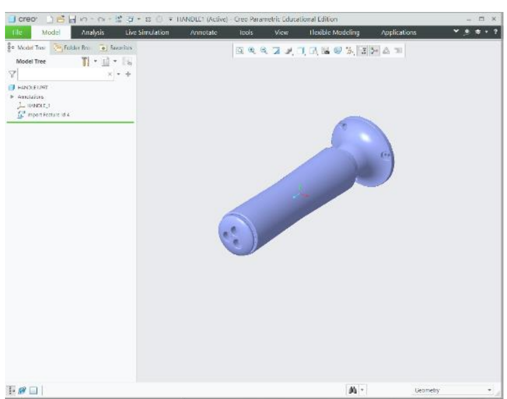
(b)



(c)



(d)



(e)

Figure 5-5 individual joints of DMRbot

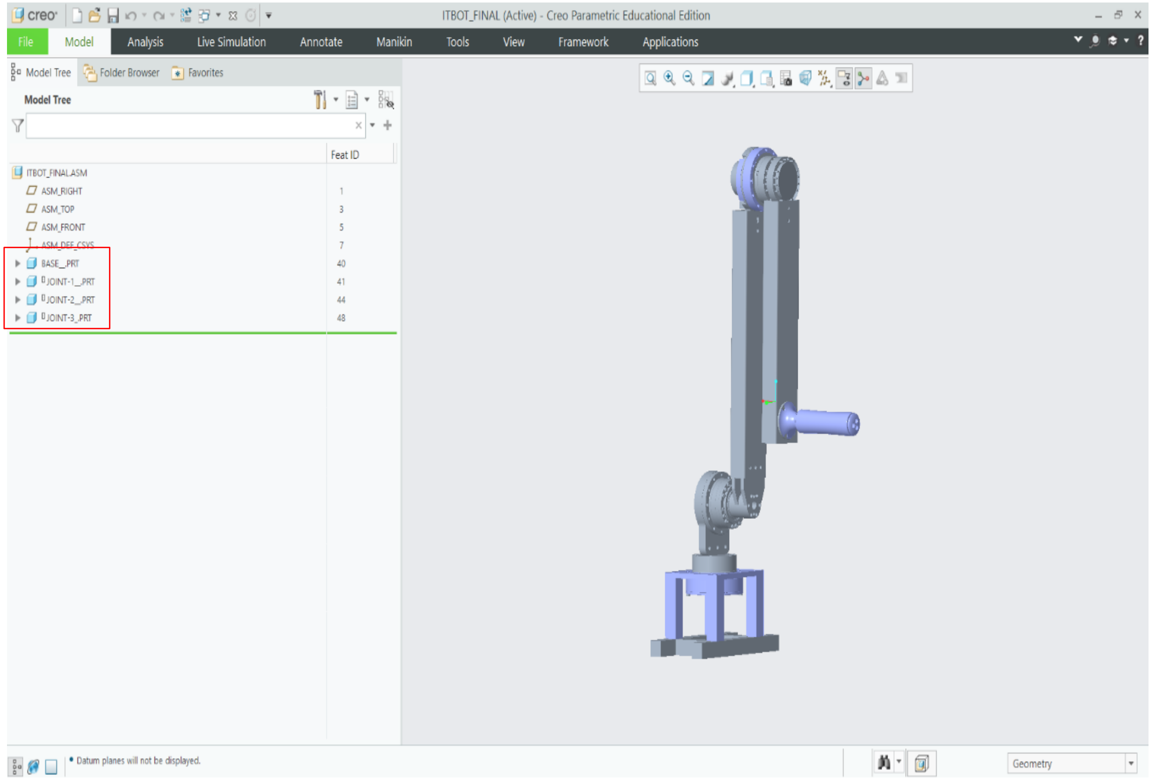


Figure 5-6: Entire assembly parts of the DMRbot

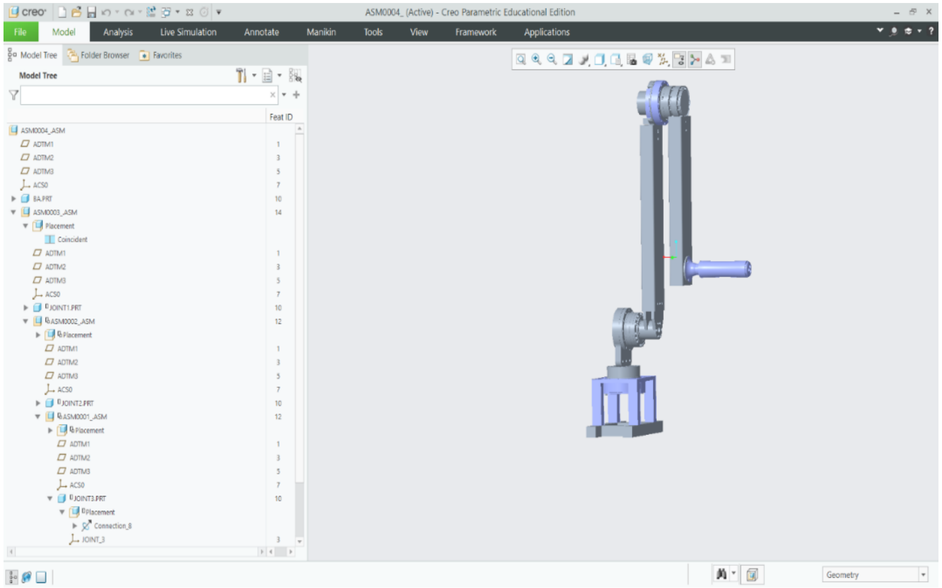


Figure 5-7: Entire subassembly parts of the DMRbot

5.5.2 Create the Model Hierarchy in Vuforia Studio

In Vuforia studio, the process of starting a new project begins with a unique project name and experience service URL. Because ThingWorx server data is necessary for AR application integration, the experience service URL is the same as the ThingWorx server URL, as shown in Figure 5-8.

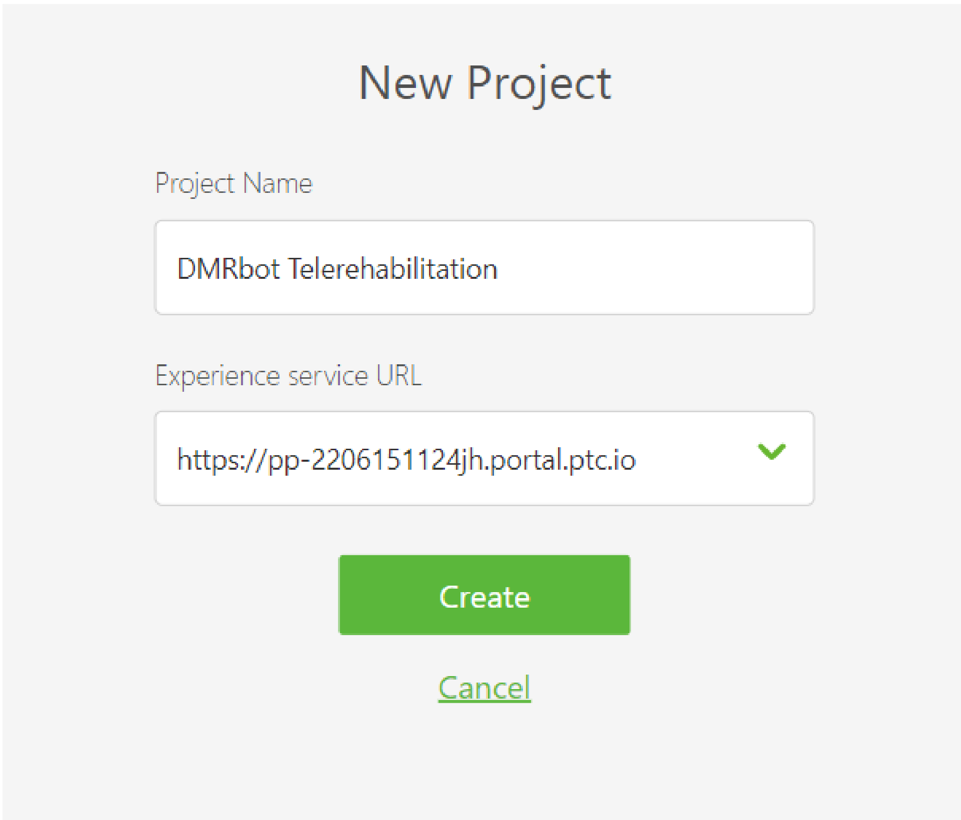


Figure 5-8: Project name and experience service URL for Vuforia Studio

After establishing a new project, the development environment is now displayed. In order to construct the robot (model) hierarchy, the CAD model of the robot must be imported into the Vuforia Studio development environment. CAD model (exported at the end of section 5.5.1) can be selected under the Properties tab by clicking on the Resource tab. Figure 5-9 shows an image of the robot model on a Vuforia Studio canvas.

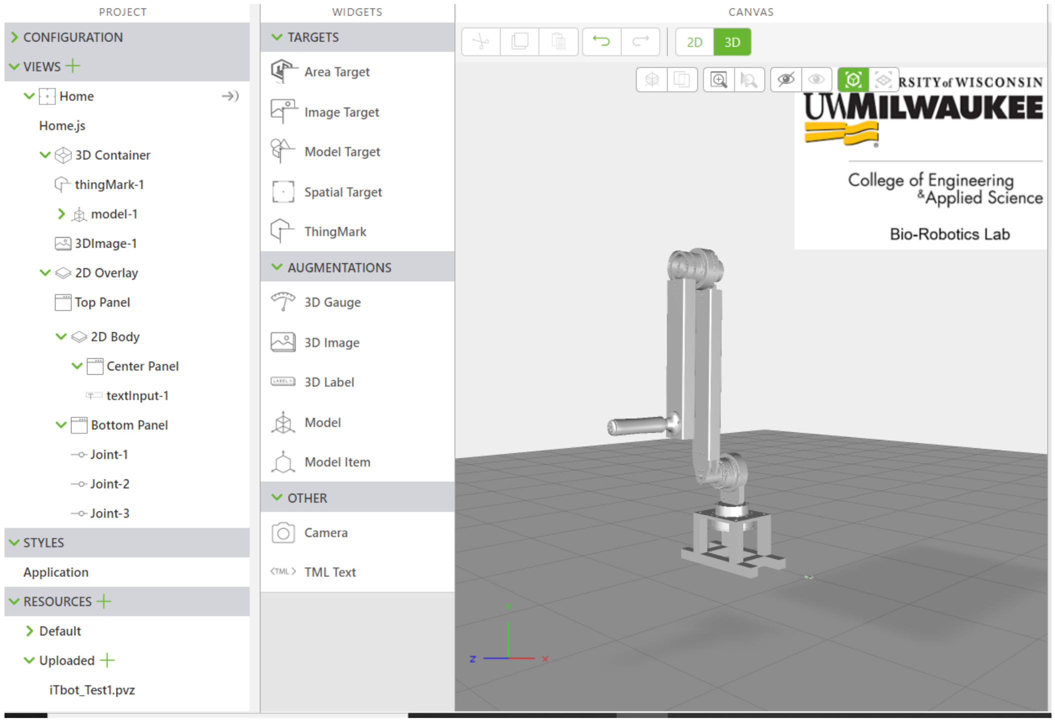


Figure 5-9: Imported robot model on Vuforia Studio canvas

The coordinates and rotations can be changed once the CAD model has been presented. The robot model assembly may be made into a hierarchical model by dragging the "Model Item" widget onto each connection. The component that is the bottom-most parent model in the robot hierarchy can be used as a starting point. Therefore, we began by dragging "Model Item" onto the base and edited the "Component Occurrence" by deleting the last values, as shown in Figure 5-10 to Figure 5-13. It can be seen that the base is the child model of the robot (model-1) parent model. The process must be done for each joint (link), starting with the ones at the bottom of the robot and moving up the hierarchy. As shown in Figure 5-10 to Figure 5-13, the child model items move automatically to nest under their parent model item. Now that the "Model" is ready, the Vuforia Studio application can be built on it.

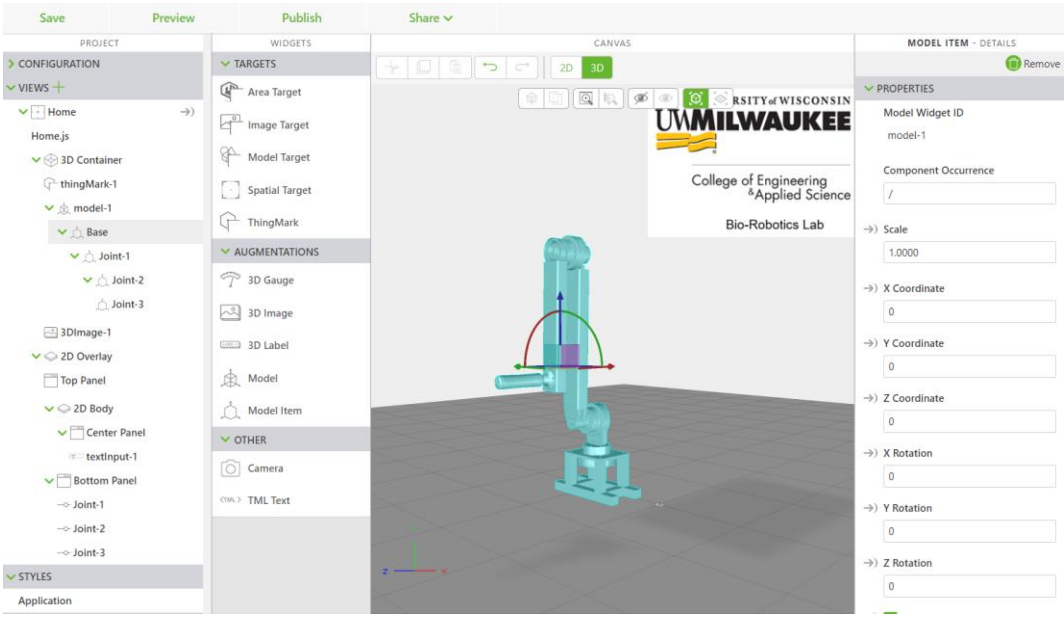


Figure 5-10: Base child model of the robot parent model

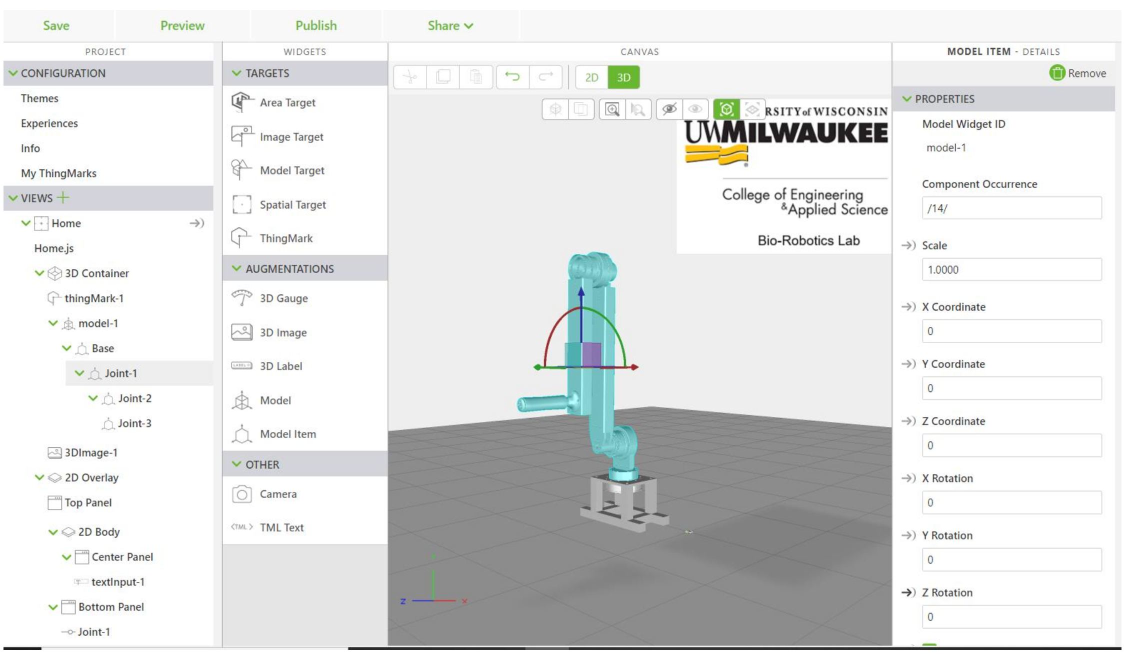


Figure 5-11: Joint-1 child model item of the base parent model

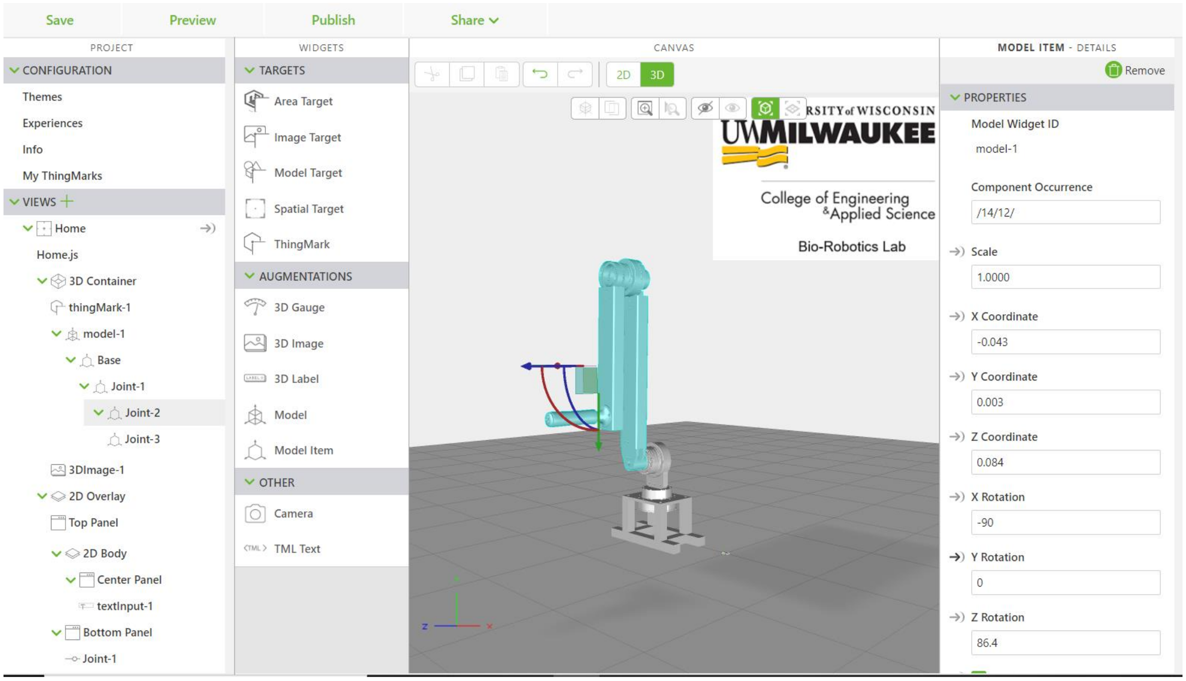


Figure 5-12: Joint-2 child model item of the joint-1 parent model

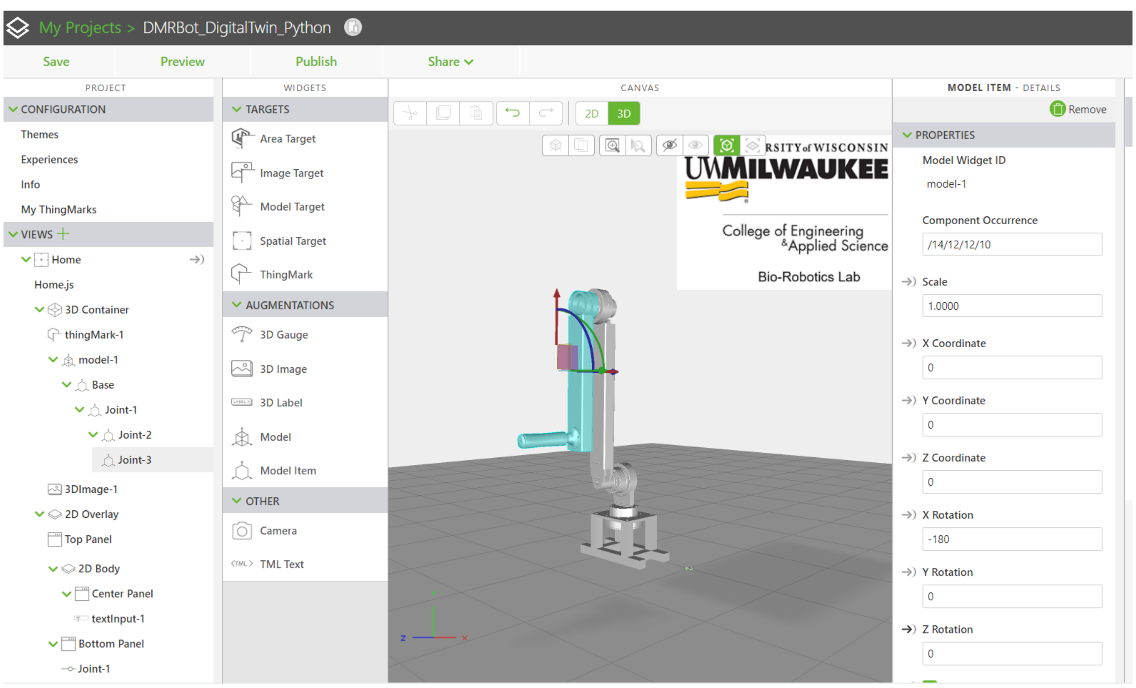


Figure 5-13: Joint-3 child model item of the joint-2 parent model

5.5.3 Vuforia Studio Application Development

It is possible to design graphical user interfaces (GUIs) for interacting with the augmented reality robot model on canvas using 2D/3D widgets while building an application for Vuforia Studio. The robot model is depicted in Figure 5-14 with a variety of 3D labels, 3D gauges, and 3D photos around it. The data is shown using the 3D label known as Augmentation (e.g., joint angles, torques, end-effector position, etc.). The technique of dragging and dropping 3D widgets on the canvas of the virtual world is the same for all the widgets.

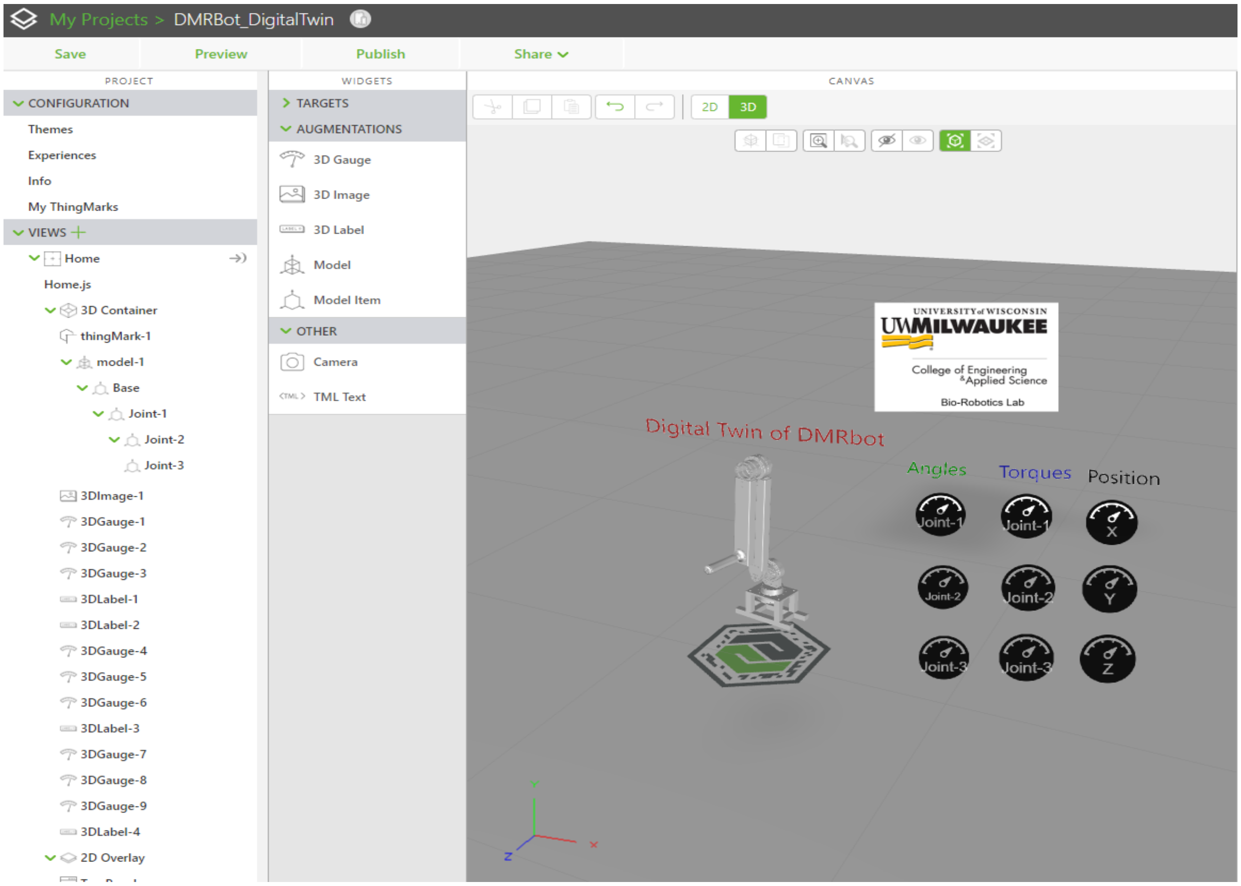


Figure 5-14: Vuforia Studio virtual environment with robot mode and 3D labels

The 2D widgets are separated into many types, such as inputs, containers, and others. The widgets in 2D inputs can be bound with model attributes in order to offer input for "Models" and "Model Items." This input can be provided by utilizing buttons, toggle buttons, sliders, and other similar widgets. Widgets from 2D Containers may be utilized for a various of purposes, including grid layout and headers. The many applications of 2D widgets on canvas are illustrated in Figure 5-15. In addition, it can be seen from Figure 5-15 that the user can rotate each joint in a clockwise or anticlockwise direction using sliders.

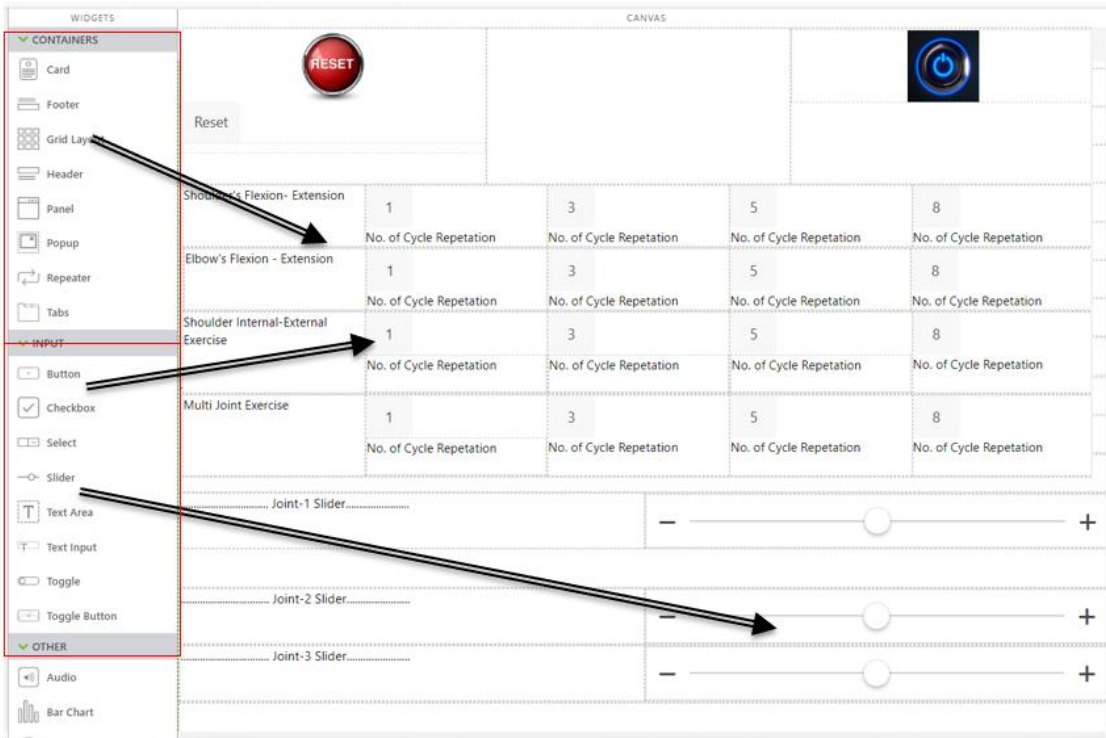


Figure 5-15: GUI developed using 2D widgets on Vuforia Studio canvas

It was stated in Digital Twin (section 5.1) that a real digital twin does not exist until the CAD model is linked to IoT data. As a result, the procedures below were followed to connect the robot model to ThingWorx IoT data. ThingWorx [8] data may be connected to both 3D and 2D widgets. As demonstrated in Figure 5-16, by clicking "+," "DMRbot Joystick" is added from ThingWorx to Vuforia Studio under the "External Data" tab. The 3D gauge widget is linked with the "J1 Angle" attribute in this case. By pressing the "Publish" button, users may access Vuforia Studio-generated projects through the experience service URL (shown in section 5.5.2) from any mobile device.

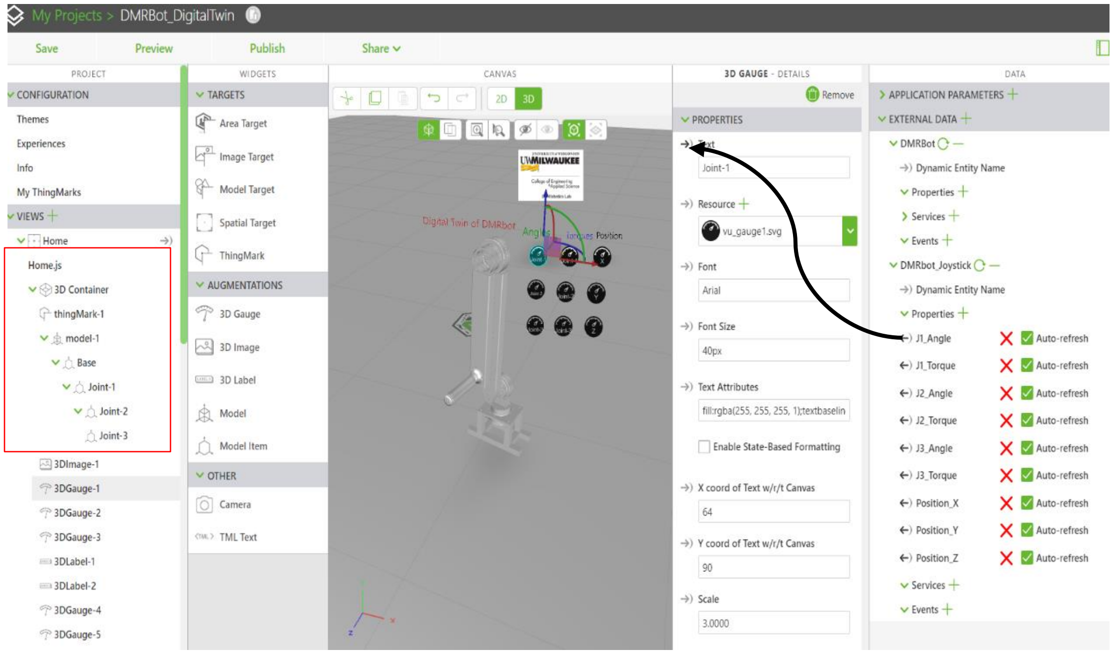


Figure 5-16: Bind 3D widgets with ThingWorx data

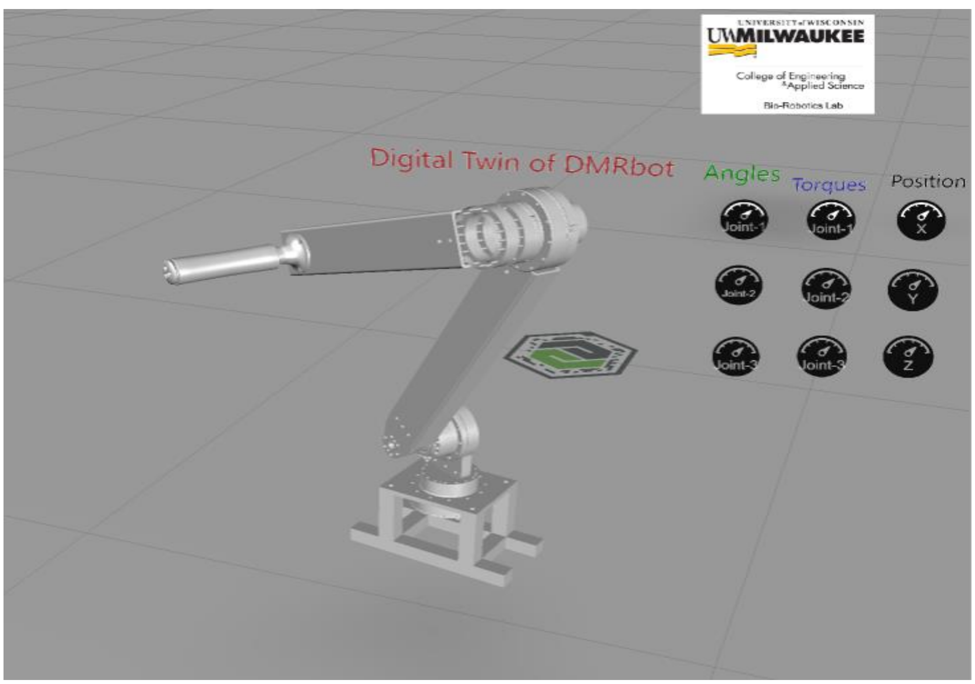


Figure 5-17: Digital Twin - Published Vuforia Studio application on experience service URL

Figure 5-17 shows the Vuforia Studio application on the experience service URL once it has been published. As a result of this step, a Digital Twin of an end-effector robot (in this case, DMRbot) is made. We made a graphical user interface so that people can interact with the digital copy of the robot and get telerehabilitation (GUI). Chapter 7, will discuss how the GUI has different telerehabilitation exercises that can be done using different control modes.

CHAPTER 6

TELEREHABILITATION FRAMEWORK

In this chapter, the telerehabilitation framework and the control architecture of telerehabilitation are discussed. The telerehabilitation framework is created utilizing Logitech Joystick as hardware and PTC ThingWorx, PTC Vuforia Studio, and PTC Vuforia View as software.

6.1 Framework Design – High Level

This section discusses the high-level telemanipulation framework design. It primarily focuses on four data flow components that connect with each other, as depicted in *Figure 6-1*: user/therapist, DMRbot, PTC ThingWorx, and PTC Vuforia Studio.

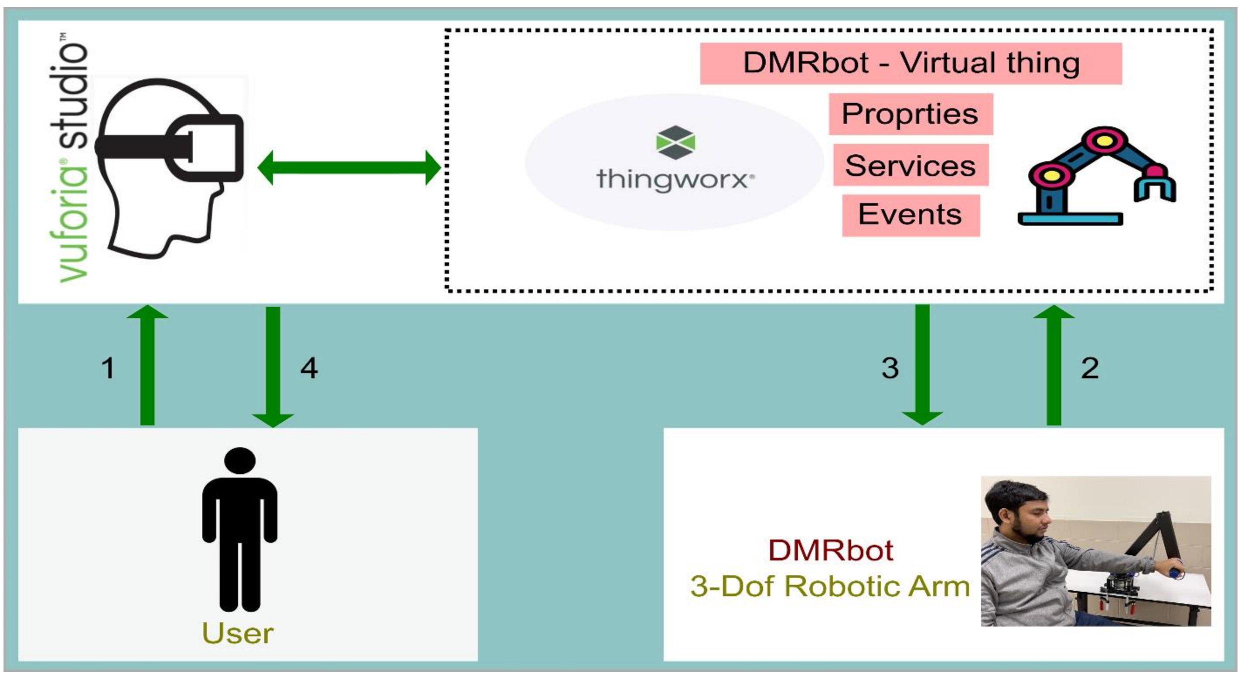


Figure 6-1 Telerehabilitation framework – high level

The figure above shows the four stages of data flow. The steps are detailed as follows:

1. The user or operator modifies the state of the DMRbot controller by interacting with an augmented reality (AR)-based DMRbot "controller" in a Vuforia Studio application. This allows the user or operator to operate the DMRbot.

2. This controller's state change is sent from the Vuforia Studio program to the ThingWorx DMRbot - virtual Thing, then from the ThingWorx DMRbot to a PC that operates the actual DMRbot. The personal computer takes in this information and then actuates the end-effector robot to conform to the new controller state.
3. The PC of the DMRbot reads the current data from the robot and transmits it to the Vuforia Studio program.
4. The user can view a distinct augmented reality of the DMRbot that represents the DMRbot's true orientation. This enables the user to confirm that the DMRbot is behaving as expected.

The physical robot has a digital twin on the Internet of Things (IIoT). The digital twin acts as a replica of the physical robot whenever it transmits actual robot data. The platform for the IIoT can be set up such that it will react to changes in the data.

6.2 Framework Design – Low Level

The proposed research is mostly about how telerehabilitation can be used, and a control framework is built and explained based on this. This section gives detailed information about the telerehabilitation control architecture at a low level. *Figure 6-2* [99] shows that the main parts of telerehabilitation's control architecture are the Robotic System and the IIoT Platform. Both parts of the system communicate with each other through the internet. The DMRbot is connected to a Client PC (Windows Computer), which provides various telerehabilitation workouts (trajectories) to the DMRbot in response to orders received from the IIoT platform.

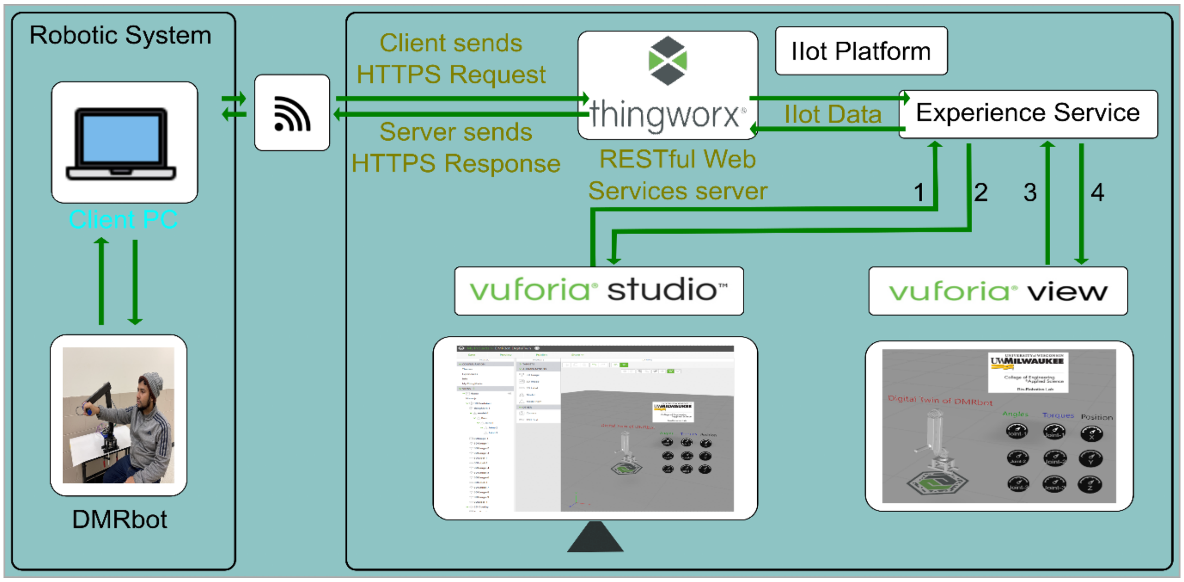


Figure 6-2 Control architecture of proposed telerehabilitation *[91]*

ThingWorx, Experience Service, Vuforia Studio, and Vuforia View are all part of the IIoT platform. ThingWorx serves as a bridge for process IIoT data transmission between the robotic system and the Vuforia Studio application in the IIoT platform (Digital Twin of a robot) field. ThingWorx server safe HTTPS protocol is used for bidirectional communication between the client PC and ThingWorx server. Client PC delivers an HTTPS request to the ThingWorx server, and the ThingWorx server responds with an HTTPS response. The 'Experience Service,' which is part of the IIoT platform (*Figure 6-2*), provides data on rehabilitation therapy. In this work, we used Vuforia Studio to create a digital twin of a robot (DMRbot) with a graphical user interface (GUI) for telerehabilitation therapy (explained in section 5.5). Vuforia Studio then publishes the generated digital twin to the Experience Service URL. We utilized the Vuforia View app to access the published GUI from the Windows/Android/iOS platforms (explained in section 6.4). The Vuforia View app is linked to the ThingWorx experience services URL. When engaging with the digital twin of a robot GUI, it communicates IIoT data to the robotic system. The benefit of adopting the ThingWorx IIoT cloud-based platform is that user therapists may manipulate the real

robot by connecting the physical joystick to the Vuforia view app. At the same time, it may see the DMRbot's motions on the AR digital twin robot. This study develops several telerehabilitation control modes, including pre-defined therapy / passive therapy, joint-control mode, and joystick-control mode. In addition, when a session begins, the therapist and patients join the Video calling room using Microsoft Teams for improved communication. In the following sections, we will cover the process of developing the proposed telerehabilitation framework, which will use PTC's ThingWorx, Vuforia Studio, Vuforia View, DMRbot, and a Logitech Joystick.

6.3 PTC ThingWorx Platform

PTC Inc. developed the ThingWorx Industrial Internet of Things (IIoT) platform. ThingWorx is a platform that offers connection, analytics, and tools for developing applications and Augmented Reality experiences. The ThingWorx platform makes achieving efficiencies simpler and quicker. It lowers the risk of activities like in-home utilities, smart cities, healthcare, and manufacturing. Obtaining and continually analyzing data that creates necessary operational data is the key to a connected system. ThingWorx offers a framework for structured and organized data in industrial IoT to manage physical assets from digital systems such as Product Lifecycle Management. ThingWorx is a platform that enables networking and analytics and provides tools for developing applications and augmented reality experiences. The "Thing Model" is the methodology that serves as the foundation for the whole ecosystem [104]. Using connectivity solutions in real-time, the "Thing Model" allows physical elements to be represented by their respective virtual representations. Mashups, which are used to convey information to a web page, may be used to get access to the ThingWorx model [105]. ThingWorx architecture is shown in Figure 6-3, demonstrating that ThingWorx is widely used in industry. In essence, the "Thing Model" is made

up of seven important principles and core components, which Josef [82] has analyzed and defined below based on the source material [104][105].

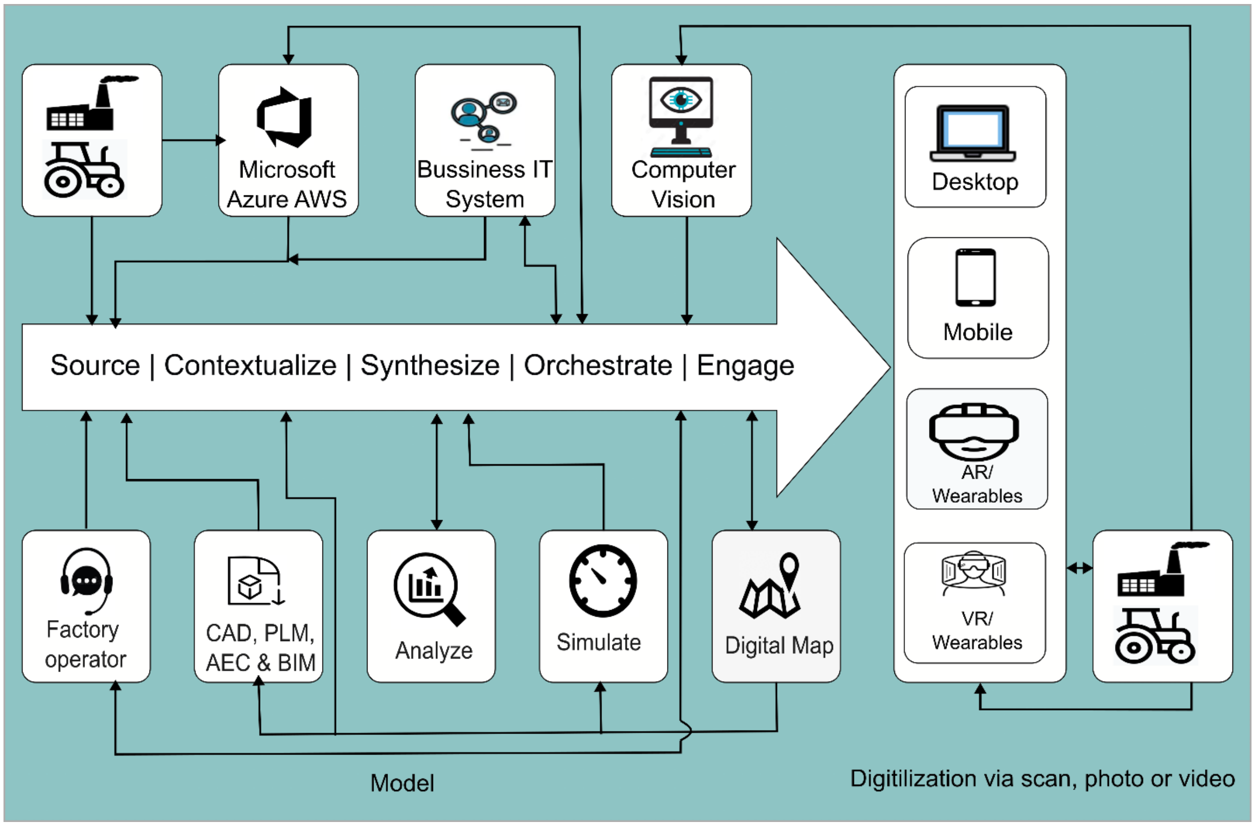


Figure 6-3: ThingWorx platform architecture [106]

- **Thing:** A Thing is a virtual data model that stands in for a real system or entity.
- **Thing Shape**: A Thing Shape is its entity class, and it has its own unique properties and operational procedures. A Thing is able to access the methods of a Thing Shape.
- **Thing** Template: A predetermined template structure that new Things can use is called a "Thing Template." This template explains the configuration and capabilities of a Thing in more detail.

- **Property**: The properties of a thing define its nature, and the properties of a thing may include a name, an explanation, and a data type. Depending on the application, properties can be either static or dynamic. In the majority of instances, physical sources, such as sensors are linked to properties through rapid communication channels. This permits virtual replication of actual values in almost real-time.
- **Services**: A Service is a function that a Thing can execute code. The ThingWorx platform provides several pre-implemented Services for various applications and Things.
- **Event**: Services and their functions are the primary sources of events. An Event is a subscribed-to, trigger-activated service that a Thing may use. A recipient of an event's data is known as a subscriber.
- **Subscription**: A Subscription is a function that runs when an Event happens. Most of the time, subscriptions and events are used together.

6.3.1 ThingWorx Composer Configuration

This section describes ThingWorx composer settings for telerehabilitation. Figure 6-4 depicts the ThingWorx composer's layout. We began by connecting "Thing" from the ThingWorx Composer to the DMRbot system using the ThingWorx REST API method.

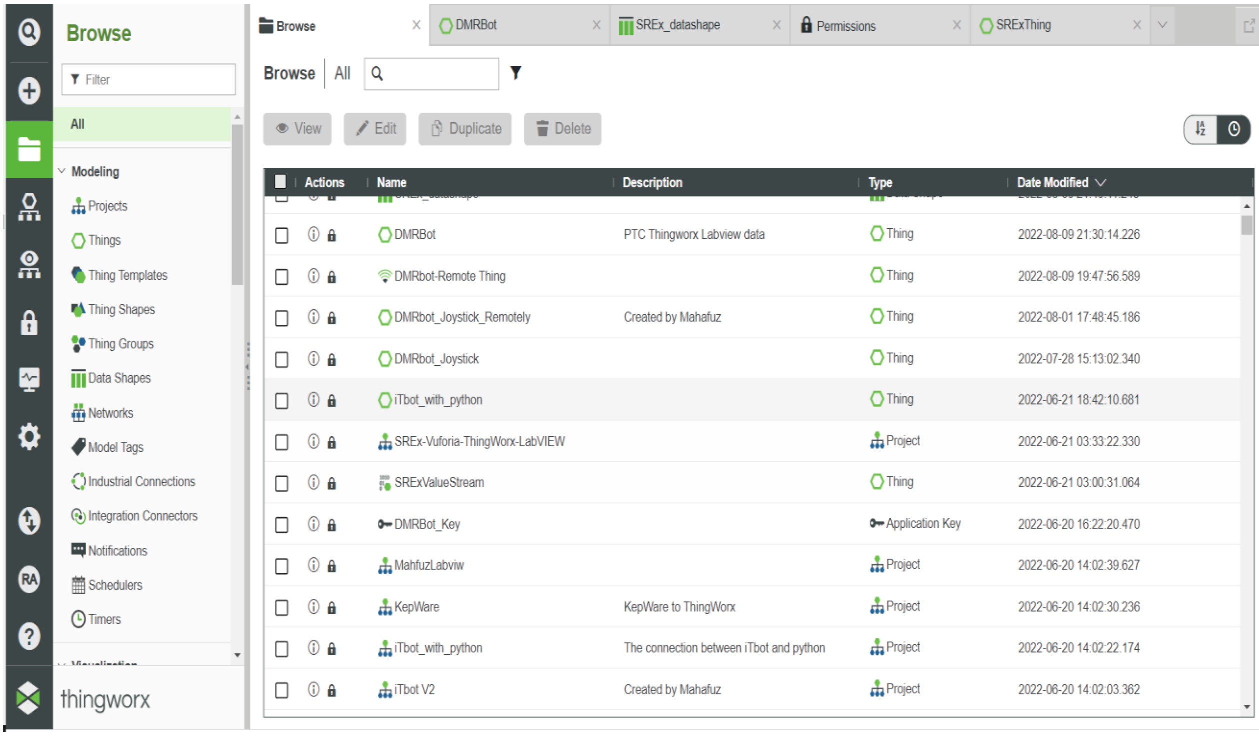


Figure 6-4: ThingWorx Composer

ThingWorx REST API was used in this research to operate the robot using Vuforia Studio/Vuforia View and display monitoring DMRbot data. In addition, we used a remote Logitech joystick and many custom settings for robot-assisted rehabilitation exercises.

- **ThingWorx URL Pattern**

  Each instance of ThingWorx has its own host and port number. It needs to be linked up to the ThingWorx instance.

  ThingWorx instance URL: https://pp-2206151124jh.portal.ptc.io/Thingworx/Composer

- **Application Key** [102]

  The application key is required to pass with ThingWorx URL to accept the request from the client. Before sending or getting data from ThingWorx, devices need to be authenticated. Each application key is given to a specific user and has the same permissions as that user [105].

For example: “293afd77-0e47-4767-b6c0-4919395652c8”

- **ThingWorx REST API** [103]

  A vital technique for communication, REST (Representational State Transfer) offers good communication for Web Services. One of the advantages of REST is that it functions without complexities and is easy to use. In addition to this, it is simple to use and may be done so by any client that is able to send an HTTP request. ThingWorx is interacted with and integrated by a substantial number of prospective customers. REST's primary objective is to improve the performance, dependability, and portability of distributed resources. [103].

- **REST API Security** [103]

  REST API Security is an essential component of the whole process of developing projects using REST APIs. The PTC suggests that for the REST API to operate, the customers must carefully review the permissions linked with it and agree to abide by it. This helps to guarantee that only authorized users are able to make use of it [103].

- **REST API Design**

  Here are some steps about the REST API call applicable to ThingWorx entities and services. REST APIs often use similar HTTP request verbs:

  - **GET** to retrieve information
  - **PUT** to change the value of an existing entity

  In this research project, we communicated with ThingWorx using Python scripts on the DMRbot computer. GET HTTP request gives us telemetry data from ThingWorx, which are then sent to the robot. The robot then delivers the received data/information to the DMRbot controller in order to complete the operation. PUT HTTP request continuously updates ThingWorx with DMRbot parameters.

6.4 PTC Vuforia View

The mobile application known as Vuforia View is a product that PTC manufactures. This software can be downloaded on Android, iOS, and Windows computers. It provides users with the ability to access and enjoy augmented reality experiences that have been built using Vuforia Studio. This augmented reality experience is loaded with 3D information and data from IIoT. [104].

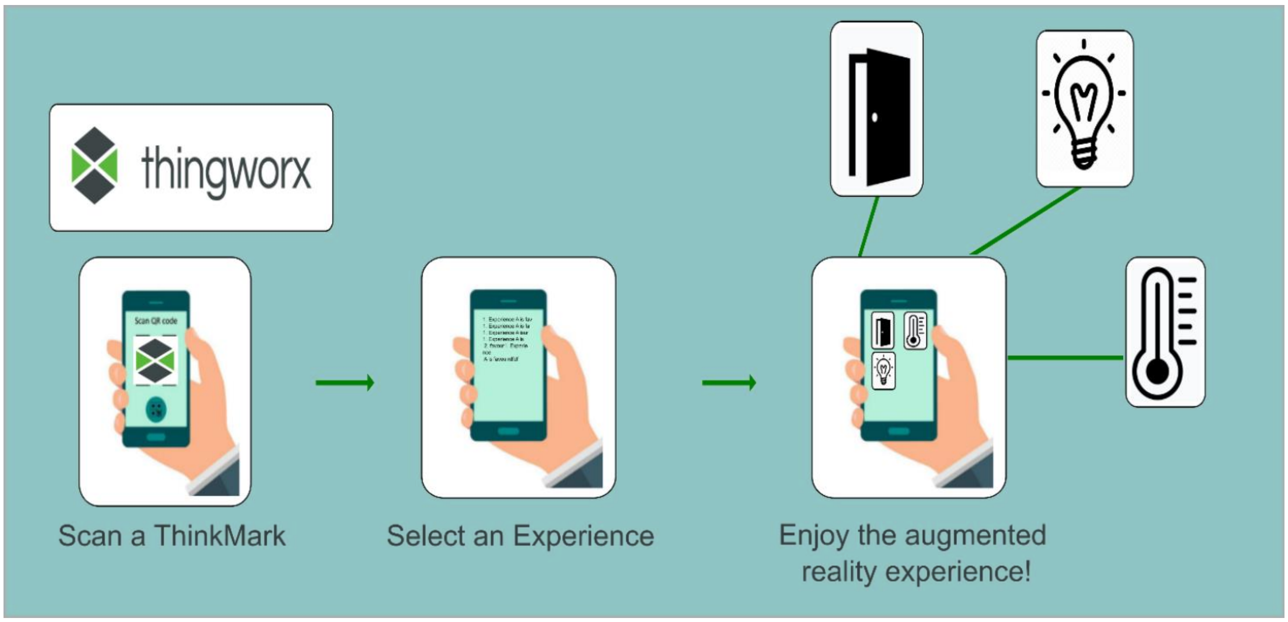


Figure 6-5: Steps for Vuforia View [105]

We follow the procedures outlined below to get access to any of the produced and published Vuforia Studio-based experiences (Figure 6-5). The ThingMark used for this research is attached in Appendix-B.

1. Open the Vuforia View app
2. Scan a ThingMark
3. Select an Experience from the list
4. Interact and enjoy the selected Augmented Reality Experience

6.5 Logitech Joystick

The Logitech G Extreme 3D Pro Joystick was employed as an additional control technique in this research to control the DMRbot's end-effector location. It contains two axes (X and Y), 12 action buttons, an eight-way hat switch, and a rapid-fire trigger. The Logitech G Extreme 3D Pro joystick [88] is shown in *Figure 6-6*, and the DMRbot end-effector coordination is shown in *Figure 6-7*. The joystick's trigger button is the primary control button, as seen in *Figure 6-6*. Always pressing the triggers is required in order to transmit and control the end-effector of the DMRbot.

The end-effector of the DMRbot can be moved along the X-axis by holding down the trigger button and pressing predefined buttons 7 and 8 in a horizontal X-axis direction. When the X-axis is moving in a positive direction, the end-effector moves to the right from the end-effector origin. When the X-axis is moving in a negative direction, the end-effector moves to the left from the end-effector origin.

By holding down the trigger button and hitting the preset buttons (9 and 10) in a horizontal Y-axis direction, the DMRbot's end-effector can be moved along the Y-axis. When the Y-axis is adjusted in a positive direction, the DMRbot's end-effector advances toward the front from its origin. When the Y-axis is shifted in a negative direction, the end-effector moves away from the starting point of the end-effector and toward the rear.

The positive Z-axis of the end-effector can be controlled by pressing and holding the trigger button and the button-3. This joystick setup moves the robot in an upward direction. The negative Z-axis of the end-effector can be controlled by pressing and holding the trigger button and the button-2. This joystick setup moves the robot in a downward direction.

Figure 6-6 Logitech Extreme 3D Pro [98]

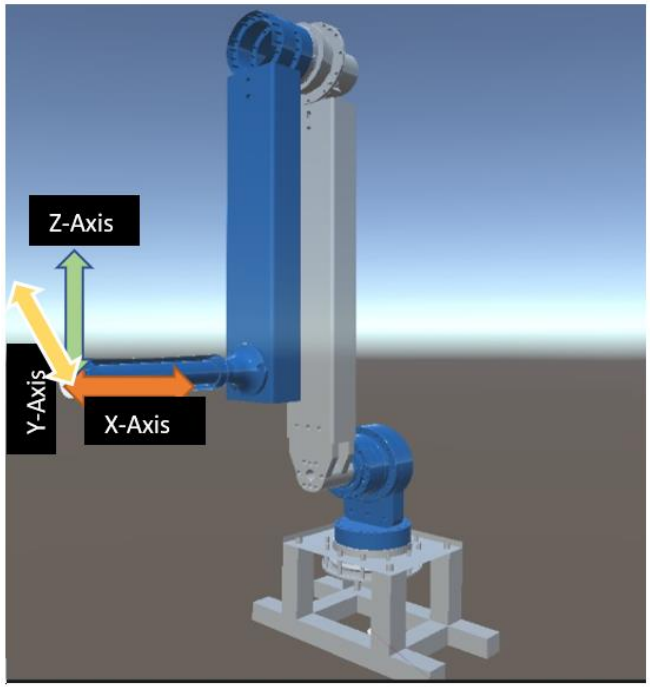


Figure 6-7 DMRbot's end-effector axis coordination

6.6 Logitech Joystick Architecture

The Logitech joystick control architecture that we designed can be shown in *Figure 6-8*. This allows us to operate the robot end-effector from a distant location. The therapist or caregiver acts as the operator and is responsible for connecting the Logitech joystick to the computer (Windows-10).

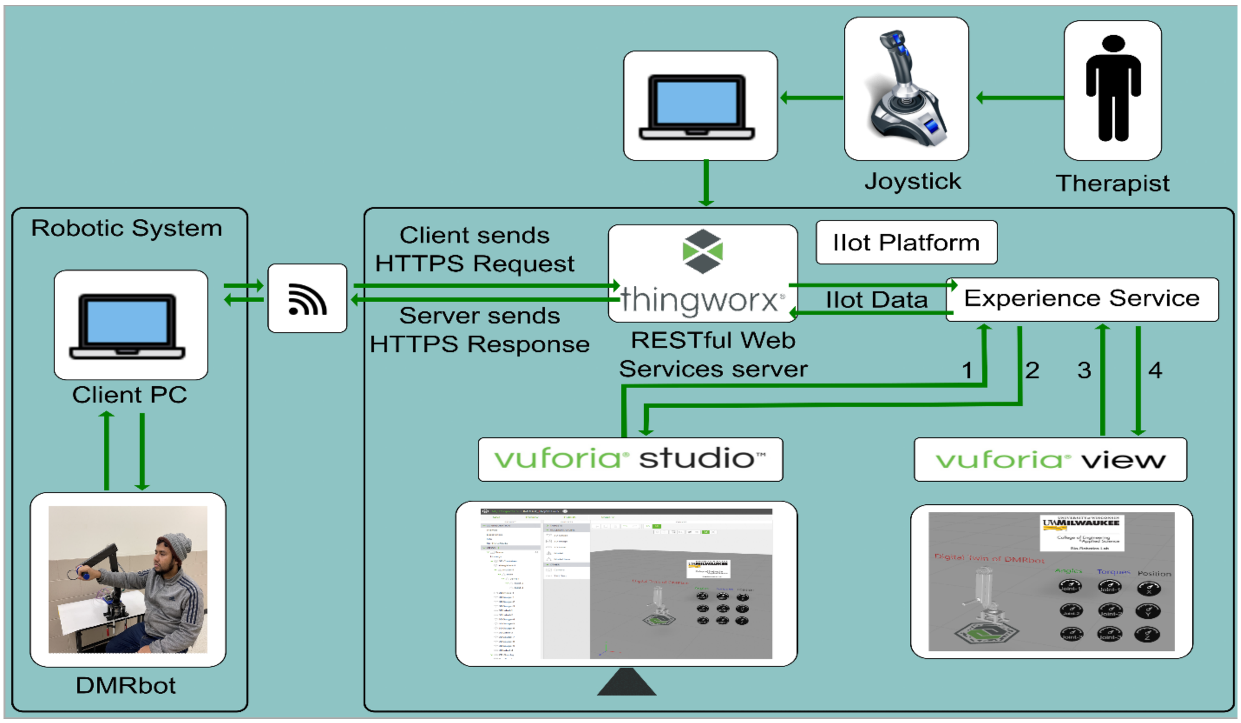


Figure 6-8 Logitech joystick architecture

Representational State Transfer Application Programming Interface (REST API) pushes the data from the joystick and is sent to the PTC ThingWorx using some Python code. After the ThingWorx platform receives the information, it is automatically interpreted and displayed in the DMRbot system and the Vuforia View/Vuforia Studio user interface. When the user hits the trigger and button 3 to move the robot in an upwards direction along the X axis, the end-effector moves

upwards with respect to the origin of the robot. Meanwhile, the AR digital twin allows the operator to keep track of the robot's progress.

CHAPTER 7

EXPERIMENTS AND RESULTS

This chapter describes the experimental outcomes used to test and evaluate the telerehabilitation framework's performance. Experiments were conducted with two healthy subjects to evaluate the feasibility and functionality of the developed robot-assisted telerehabilitation system. This chapter begins with an overview of the experimental setting, including human-robot collaboration. The DMRbot was used to perform passive rehabilitation exercises using the developed telerehabilitation framework. Throughout the experiments, the robot's joints, torque, velocity, and positions are measured and compared to the DMRbot's digital twin. The experimental findings indicate that the developed telerehabilitation framework can be utilized successfully to deliver telerehabilitation exercises for the upper limb utilizing a rehabilitation robot.

7.1 Experimental Setup

The experimental configuration of the telerehabilitation system involves two sides of arrangements: the operator or therapist and the participants. *Figure 7-1* depicts the experimental setup from the operator's perspective, in which an operator and participant communicate in a video conference using Microsoft Teams. An operator can view and communicate with each participant while providing a variety of passive rehab rehabilitation exercises utilizing this video session (using pre-defined trajectory parameters). To provide a variety of passive rehab exercises, the therapy modes must be modified; to do so, an operator utilizes the Vuforia View app for iPad, as seen in *Figure 7-1* (made using Vuforia Studio 3D/2D widgets). As seen in *Figure 7-1,* an operator employs the developed digital twin of an end-effector robot to follow the robot's movements with low latency and monitor the participant's input while interacting with the robot.

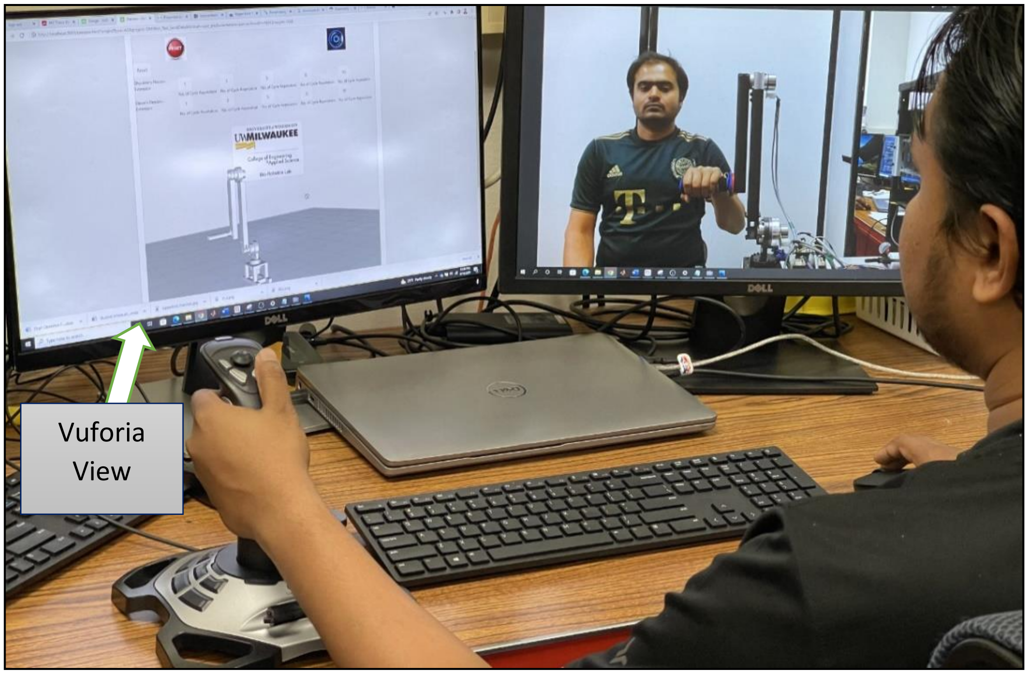


Figure 7-1 An experimental setup on the operator's end

Figure 7-2 depicts the participant's side of the experimental setup, which includes communication devices and human-robot interaction.

The experimental setup for the DMRbot system consists of the robot in a desktop configuration. The DMRbot can be used for both handed (right-handed and left-handed). As illustrated in *Figure 7-2*, the DMRbot system was established on a desktop to deliver telerehabilitation exercises. Experiments involved healthy participants sitting on a chair at a specified distance from the desktop. During experiments, participants hold the end-effector position of the robot using a commercially available wrist glov. We utilized a camera, monitor, and Microsoft Teams to connect with operators during therapy sessions to record upper arm movements during rehabilitation exercises.

Two healthy individuals (25–28 years old, 1.60–1.80 m tall, 65–80 kg) performed different exercises to test the developed telerehabilitation systems. We created a use case scenario for

telerehabilitation by separating the participant's and operator's systems. In our tests, the robotic system and IIoT platform experienced 180ms latency.

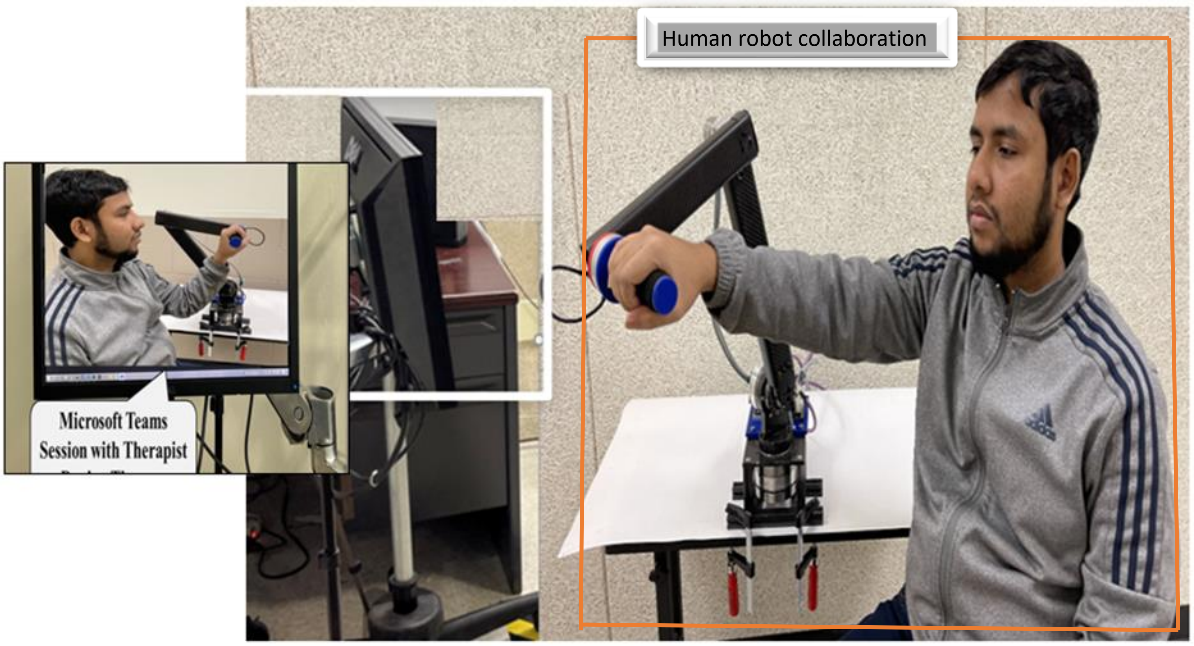


Figure 7-2 An experimental setup on the participant's end

We developed three modes to provide different telerehabilitation exercises, including-

(i) Passive Rehab Exercise (PRE) mode using Pre-determined Trajectory,

(ii) Interactive Real-Time TeleRehabilitation Exercise Mode, i.e., Controlling Individual Joints of the Robot to Provide PRE, and

(iii) Interactive Real-Time TeleRehabilitation Exercise Mode, Controlling Robots' End-Effector Position using a Joystick to provide PRE.

The operator can change different exercise methods/modes during experiments using the Vuforia View user interface, as illustrated in *Figure 7-3*. Each kind of exercise has its own user interface.

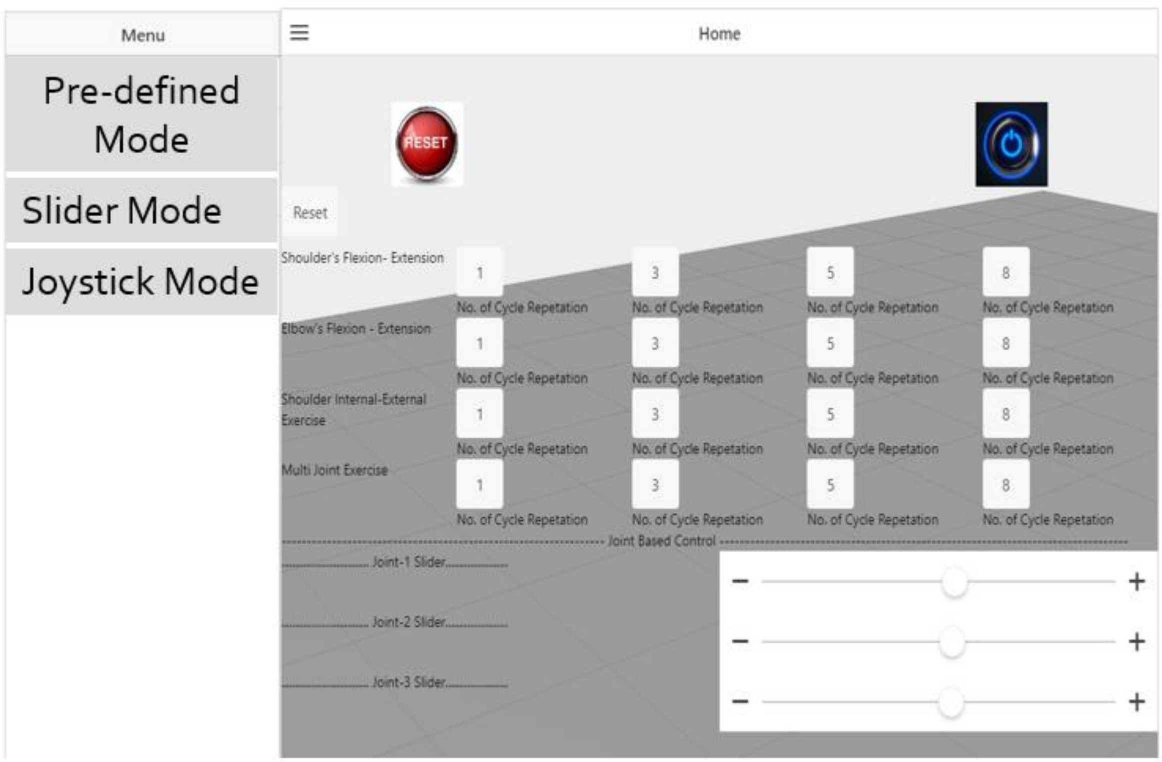


Figure 7-3 Telerehabilitation Vuforia View app in iPad

7.2. Passive Rehab Exercise (PRE) Mode Using Pre-Determined Trajectory

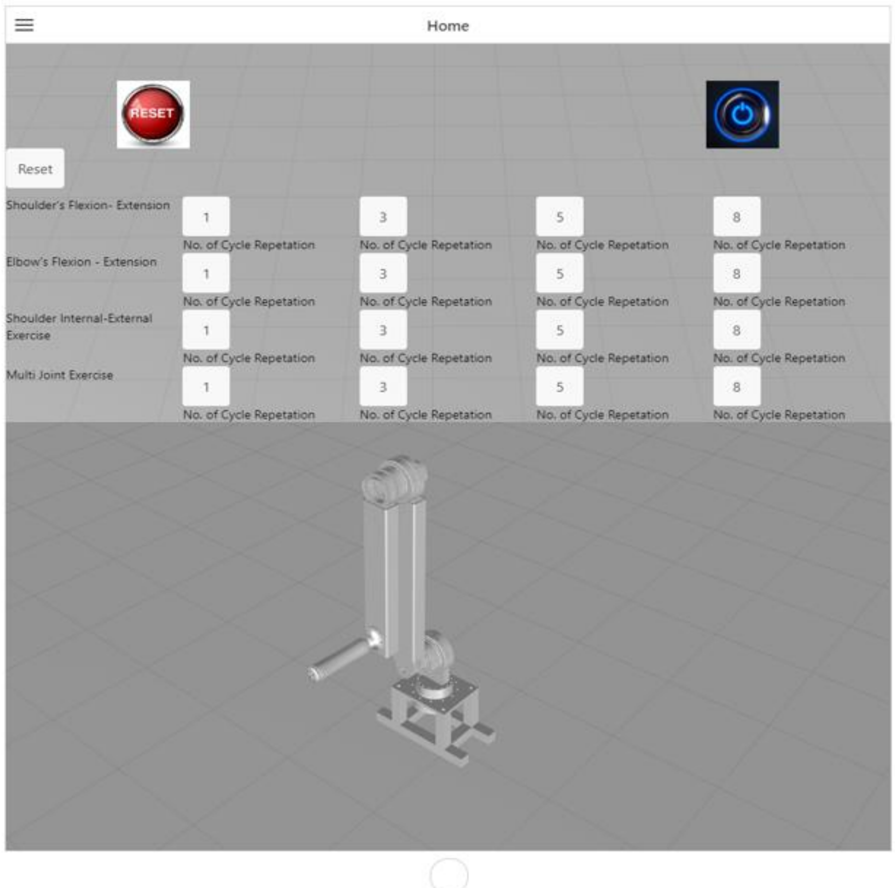


Figure 7-4 Augmented reality user interface for a passive mode of telerehabilitation exercises.

In Passive rehabilitation exercises, the participants do not actively participate during the exercise session, as they are incapable of moving their arms. Here, the exercises focused on the movement of each joint in the upper limb, including the shoulder and elbow. However, it is later observed that in an end-effector type robot, like the DMRbot, where the user's arm is not constrained, this trajectory results in multi-joints (i.e., shoulder, elbow, and wrist joints) motion of the arm. The goal of this exercise is to increase participant's range of motion. In passive rehabilitation exercise,

the DMRbot moves participants arms in 3D space, mainly to reduce spasticity and increase range of motion. Also, all exercises can be done again by clicking the number of repetitions under each exercise and keeping an eye on the AR digital twin. The most preferred trajectories are:

- **Elbow Flexion – Extension**

To provide this exercise, As shown in Figure 7-5, during the flexion-extension exercise, the robot's joints are moved as follows:

- Joint-1 stays in its initial position (0^o);
- Joint-2 moves from its initial position (0^o) to -15°, and finally returns to its initial position;
- Joint-3 moves from its initial position (0^o) to 80°, and finally returns to its initial position;

The experiment uses five repetitions.

Figure 7-5 shows a participant seated on the chair, holding the robot's end-effector (handle) and facing the Microsoft Team's screen to see the elbow joint flexion-extension exercise.

Figure 7-5: Participant sitting position during elbow joint flexion-extension exercise.

Figure 7-6 shows the robot's joint angles, velocities, and torques. Figure 7-7 shows the end-effector's position and the IIoT-based monitoring robot moments on the AR robot.

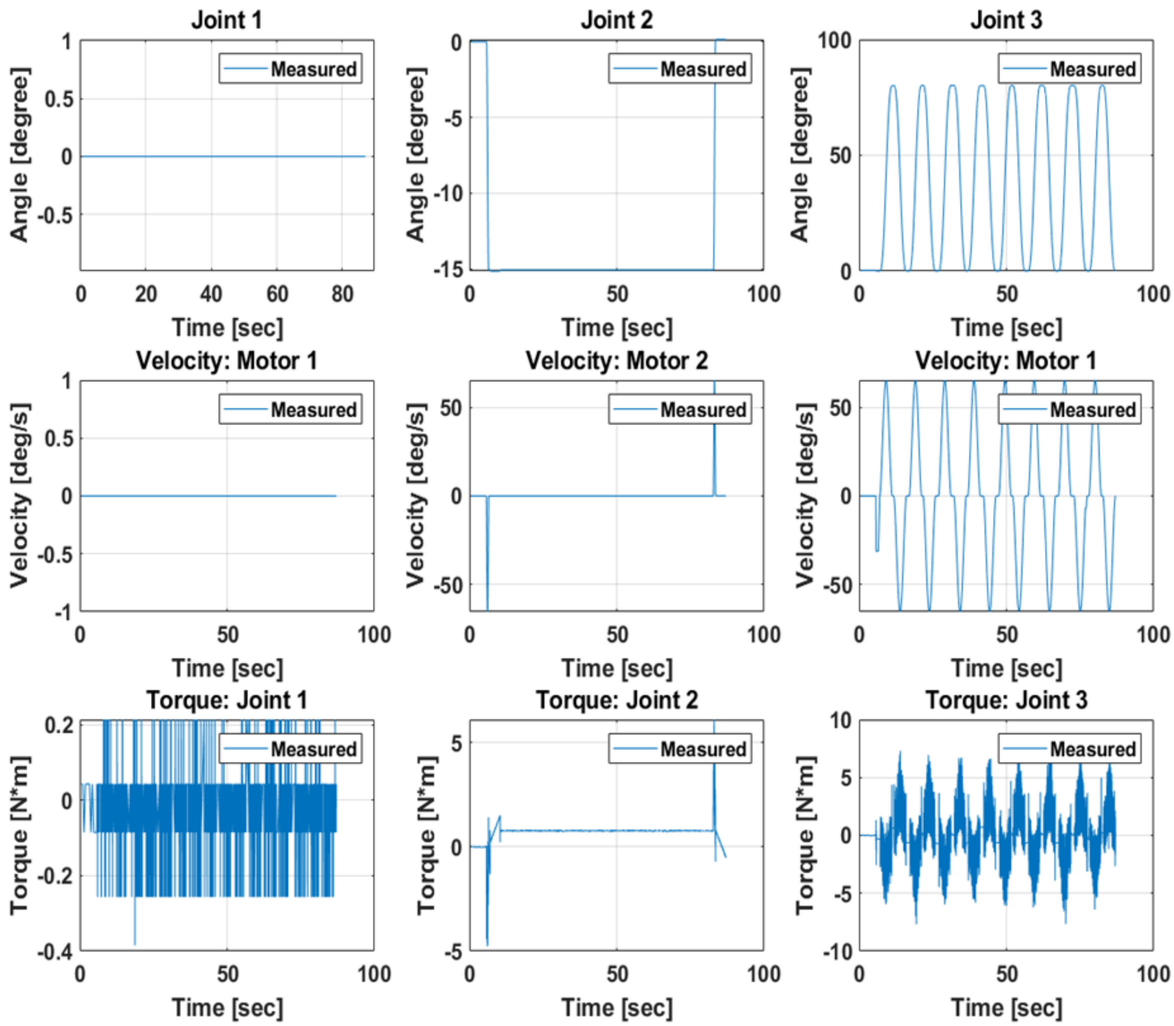


Figure 7-6: DMRot's joint angles, velocities, and torques during elbow joint flexion-extension exercise.

Figure 7-7: Monitoring elbow joint flexion-extension exercise using Vuforia Studio AR platform and observing participant's upper-limb movement through Microsoft Teams video session.

- **Shoulder Flexion – Extension**

As shown in Figure 7-8, a participant is seated on the chair, holding the robot's end-effector (handle) and facing the MS team's screen to see the shoulder joint flexion-extension exercise. The robot's joints are moved in the following ways during the flexion-extension exercise:

– Joint-1 moves from its initial position (0^o) to 10°, then 10° to -10° and finally returns to 0^o;

– Joint-2 moves from its initial position (0^o) to -20°, and stays at it for around 8 sec, then moves from -20° to -45° and finally returns to its initial position;

– Joint-3 moves from its initial position (0º) to -90° and finally returns to its initial position;

The experiment uses three repetitions.

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Figure 7-9 shows the DMRbot' joint angles, velocities, and torque during experiment. In contrast, Figure 7-10 shows the robot's end effector position and IIoT-based monitoring of AR digital twin of the in the AR platform.

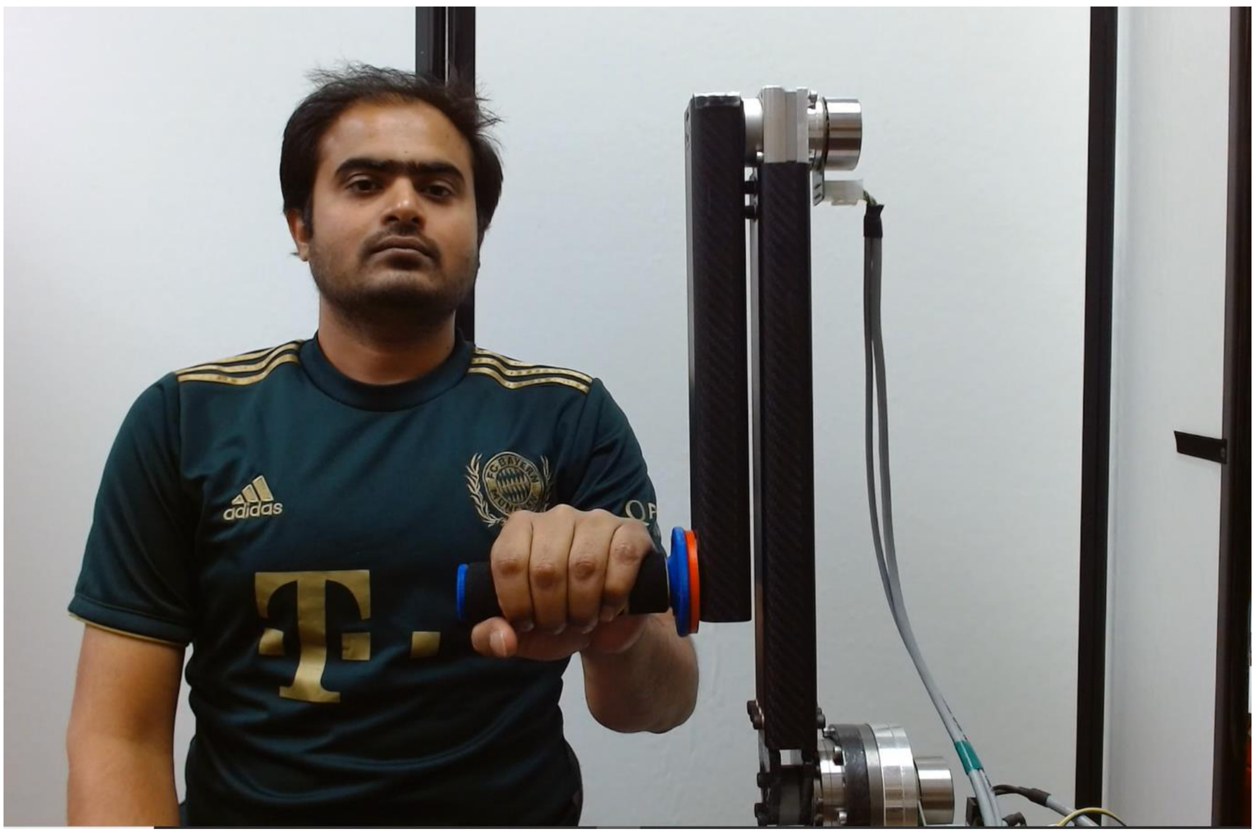

Figure 7-8: Participant sitting position during shoulder joint flexion-extension exercise

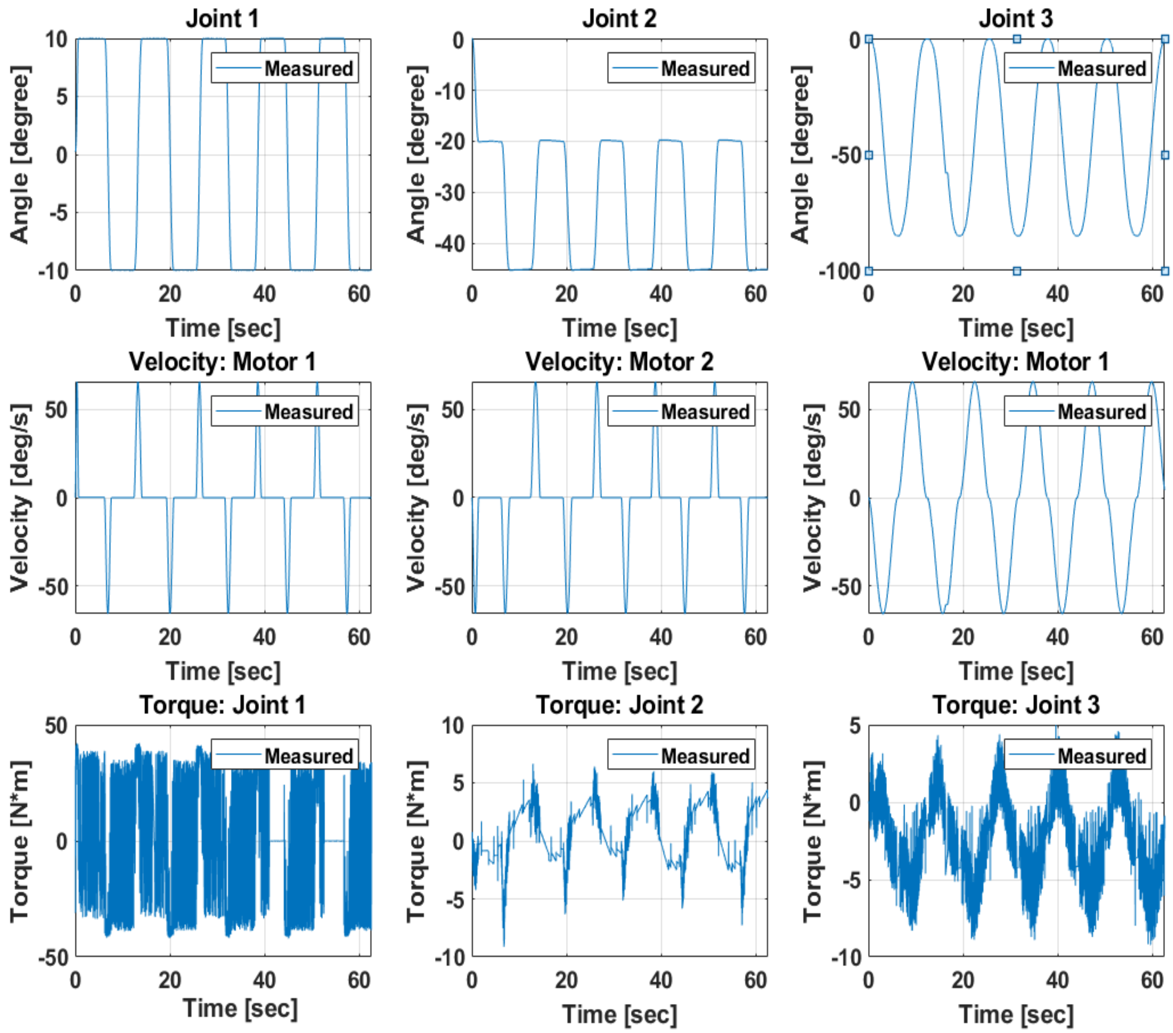

Figure 7-9: DMRbot's joint angles, velocities, and torques, during shoulder joint Flexion - Extension Rotation exercise.

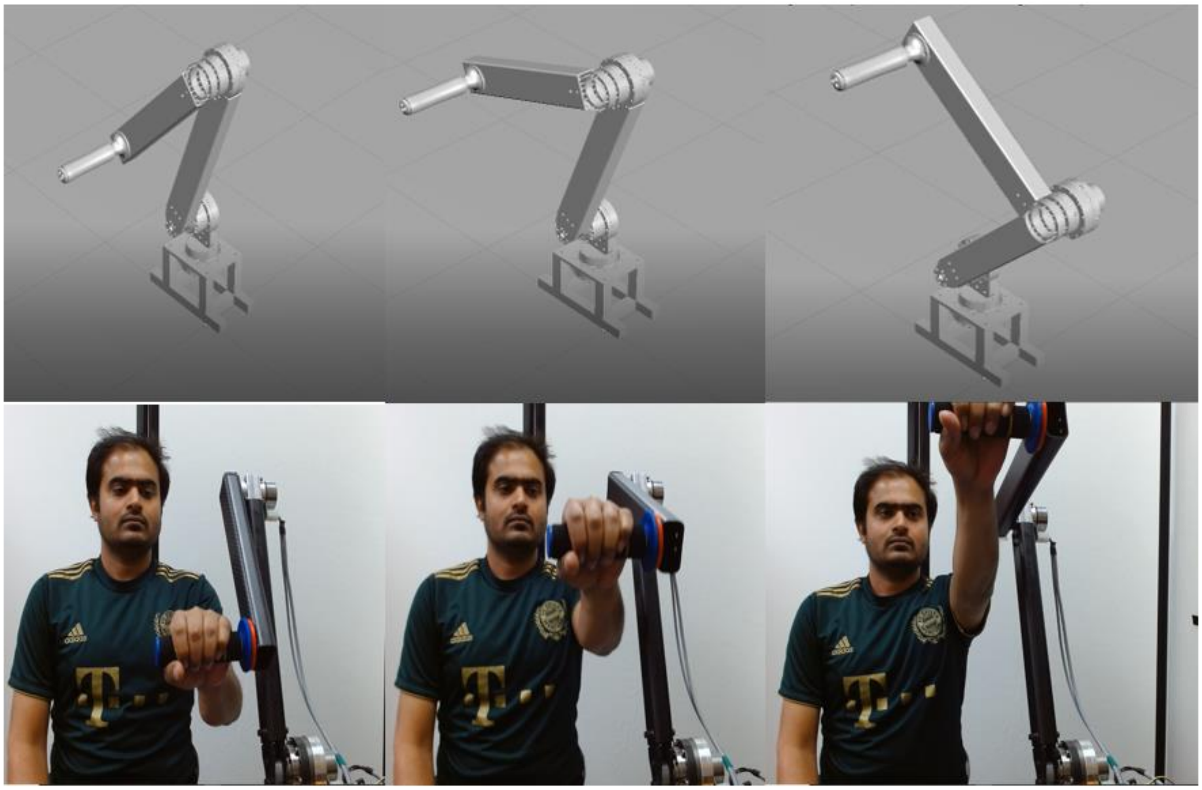

Figure 7-10: Monitoring shoulder joint flexion-extension exercise using Vuforia Studio AR platform and observing participant's upper-limb movement through Microsoft Teams video session.

- **Multi Joint Exercise**

For this exercise, the experiments were conducted with both subjects. Initially we experimented with subject-A (age:28 years; height: 1.63m; weight: 68 kg) where the subject held the robot's handle, as shown in Figure 7-12, with the right hand. During the multi-joint exercise, the robot's joints are moved in the following ways to give this exercise:

- Joint-1 moves from its initial position (0^o) to -30°, then -30° to 15° and finally returns to its initial position;

– Joint-2 moves from its initial position (0º) to -35°, 35°, -35°, and finally returns to its initial position;

– Joint-3 moves from its initial position (0º) to 80°, and finally returns to its initial position;

The experiment uses three repetitions.

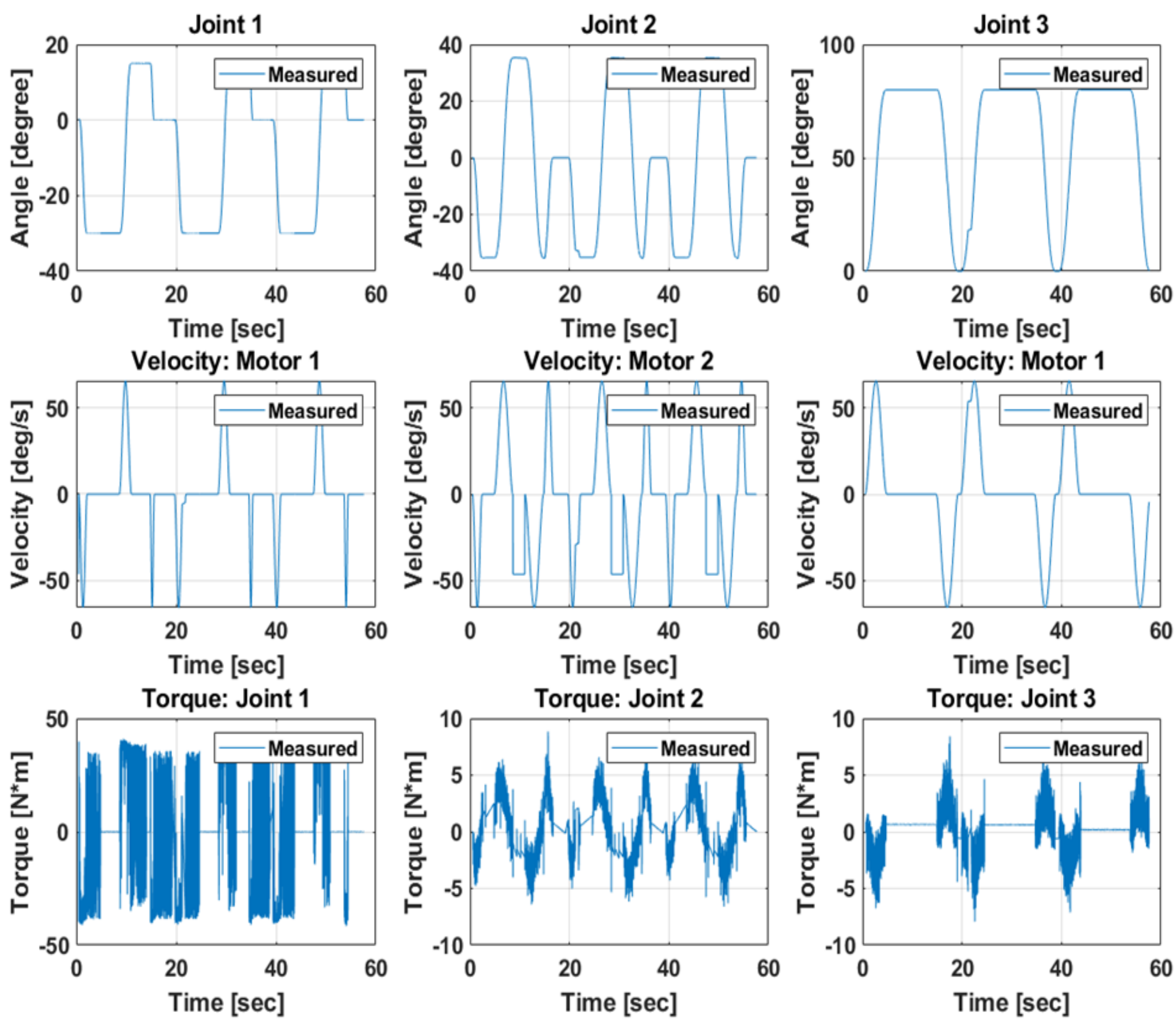

Figure 7-11 DMRbot's joint angles, velocities and torques during multi-joint exercise for subject-A.

Figure 7-12: Monitoring Multi-Joint exercise on AR digital twin and observing participants upper-limb movement through Microsoft Teams video session

Subject-B (age:26 years; height: 1.67m; weights: 80 kg) in the experiment used his left hand to hold the robot, as shown in Figure 7-14. During the multi-joint exercise, the robot's joints are moved in the following ways to give this exercise:

- Joint-1 moves from its initial position (0^o) to 15°, then 15° to -45° and finally returns to 0^o;
- Joint-2 moves from its initial position (0^o) to 20°, then to 18° and finally returns to its initial position;
- Joint-3 moves from its initial position (0^o) to -80° and finally returns to its initial position;

The experiment uses two repetitions.

Figure 7-13 shows the DMRbot's joint angles, velocities, and torque during the experiment. In contrast, Figure 7-14 shows the robot's end-effector position and IIoT-based monitoring of the AR digital twin of the robot in the AR platform.

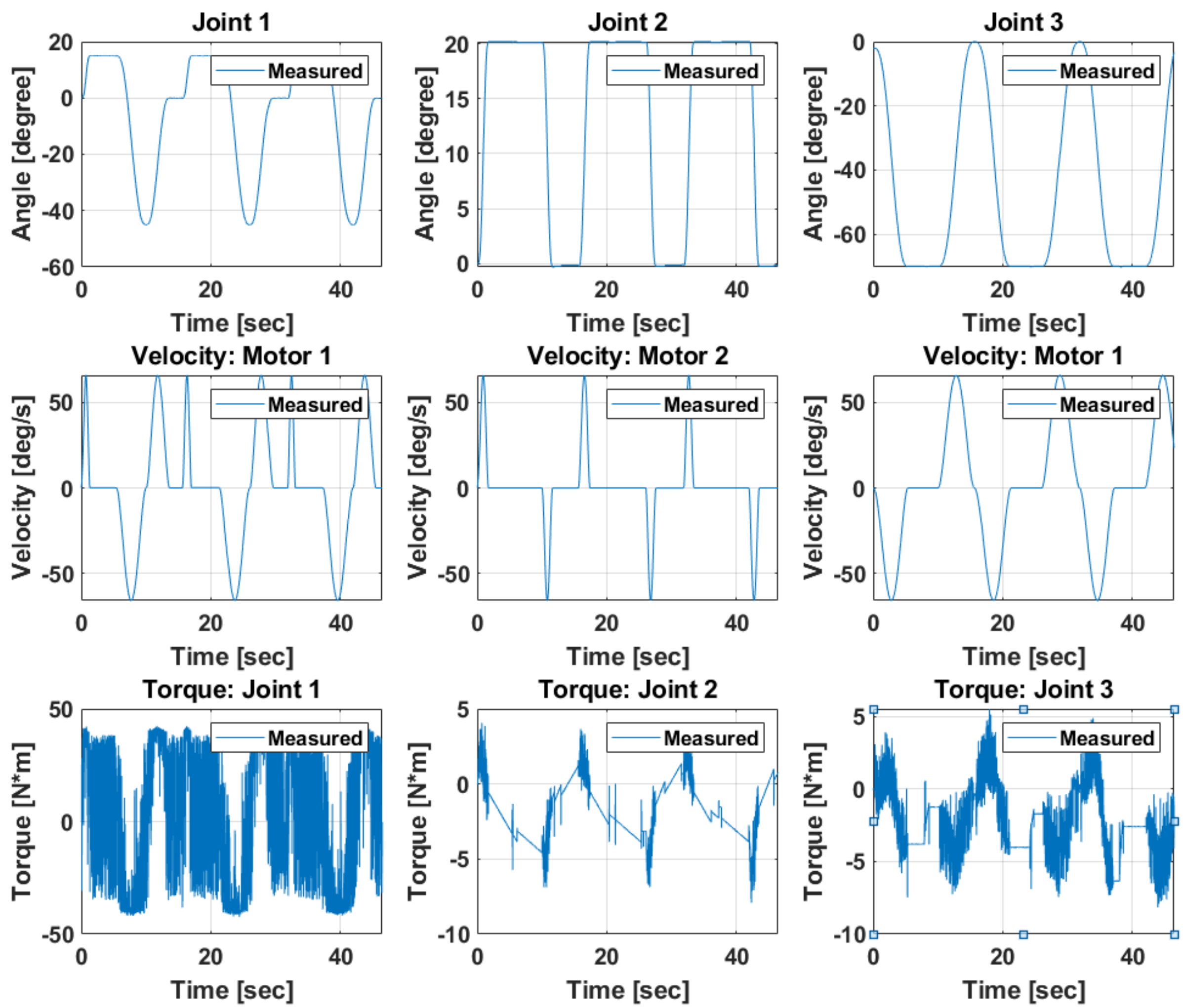

Figure 7-13 DMRbot's joint angles, velocities, and torques during multi-joint exercise for subject-B.

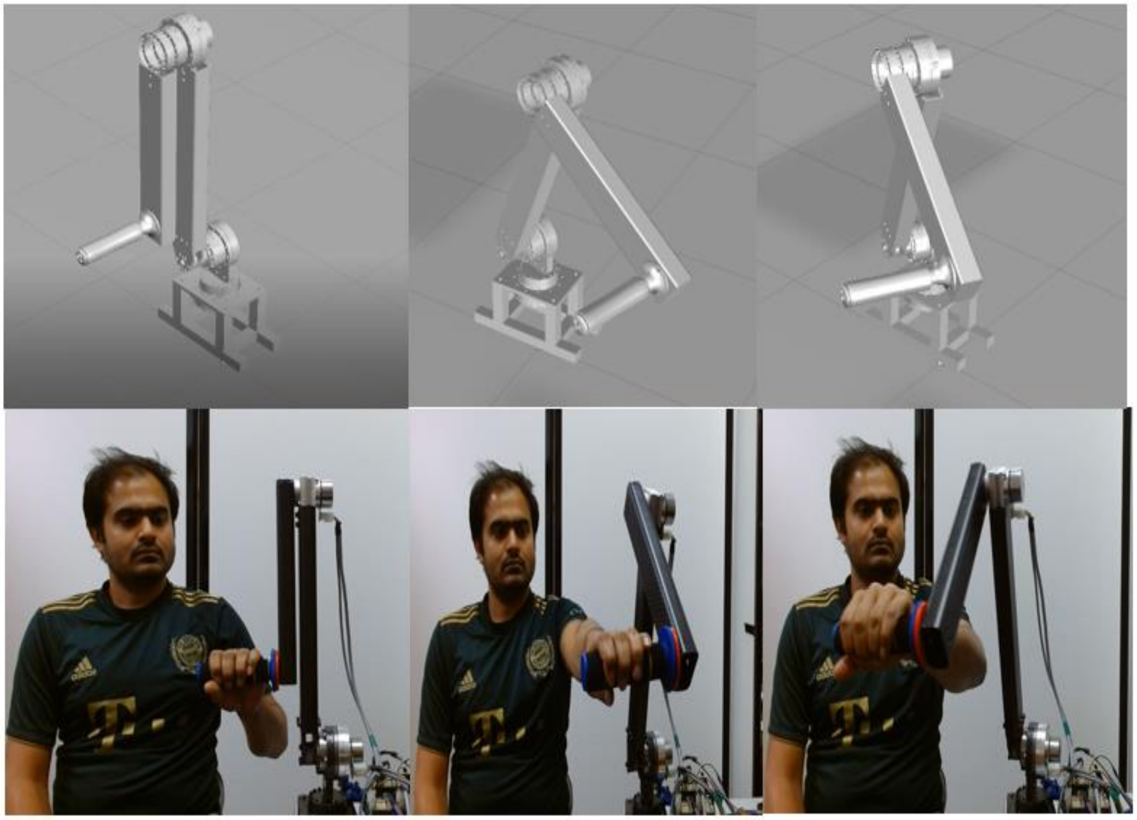

Figure 7-14: Monitoring multi-joint exercise using Vuforia Studio AR platform and observing participant's upper-limb movement through Microsoft Teams video session.

7.2 Interactive Real-Time (RT) Control of Individual Joints of the Robot for TeleRehabilitation Exercise (TRE)

Figure 7-15 depicts an augmented reality (AR) user interface for telerehabilitation exercises in the RT mode. Unlike previous therapeutic control modes, when the robot's end-effector motion was controlled to provide PRE, individual joints of the robot can be controlled via the Vuforia user

interface to conduct Telerehabilitation exercises in this mode (PRE). In this mode, the Vuforia user interface can be used to control the robot's individual joints to do Telerehabilitation exercises (PRE). Through this user interface, the operator can move sliders on the positive or negative side to turn the robot joint clockwise or counterclockwise. Also, the "Reset" button lets the rehab device start from where the robot was at its initial position (zero degrees for all three joints).

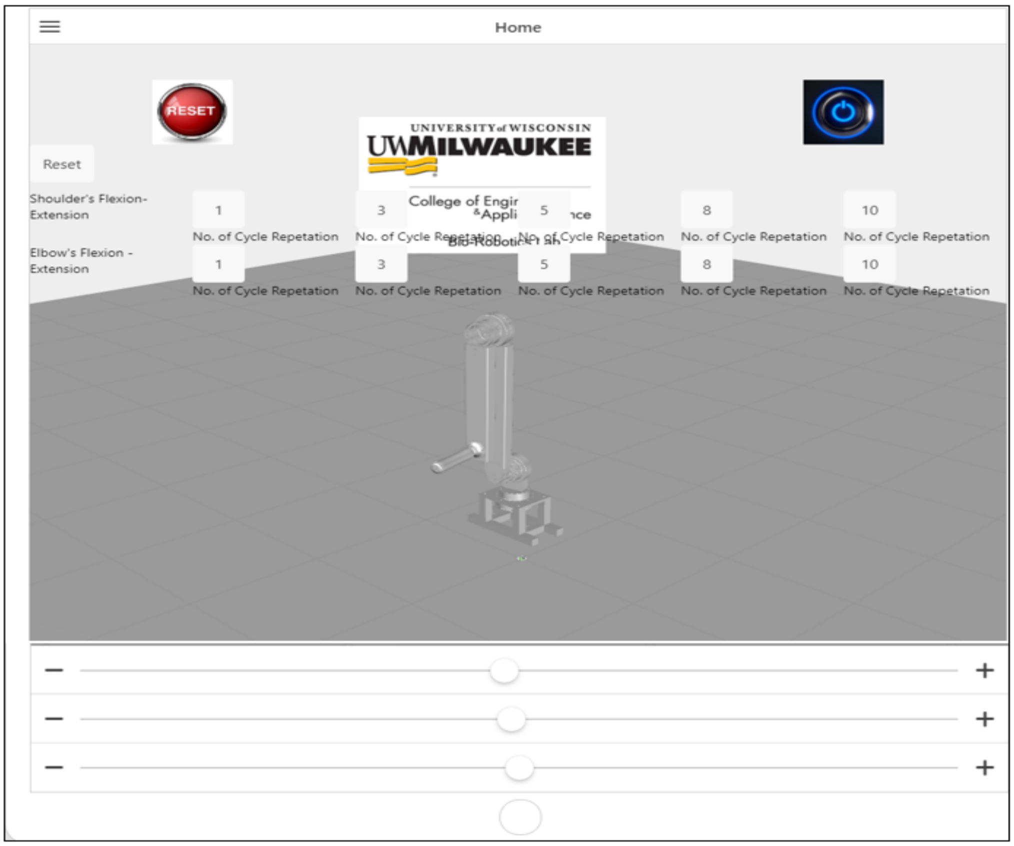

Figure 7-15: Augmented reality user interface for RT mode of telerehabilitation exercises.

We performed this RT mode with two different participants. This mode provides multi-joint PRE for the upper limb's joints. As shown in *Figure 7-2*, like in previous exercises, during the real-time mode, participants are seated on the chair at a convenient distance from the desktop, holding the

robot's end-effector (handle), and receive PRE where an operator controls the individuals joint pf the robot using the slider.

The robot joints are reset to zero angles for participant-1. Figure 7-16 and Figure 7-17 show the results from the multi-joint PRE experiment. In order to do this exercise, the operator manipulates the robot joints in the following ways using the slider from Vuforia's user interface:

- Joint-1 only moves from its initial position (0^o) to 16^o and stays there for around 12 sec, and then it returns to 0^o;
- Joint-2 moves from its position to -33^o and stays at -33^o for about approximately 8 sec, and then it returns to 0^o;
- Joint-3 moves from its initial position (0^o) to -85^o and stays at -85^o for approximately 12 sec, and finally returns to its initial position;

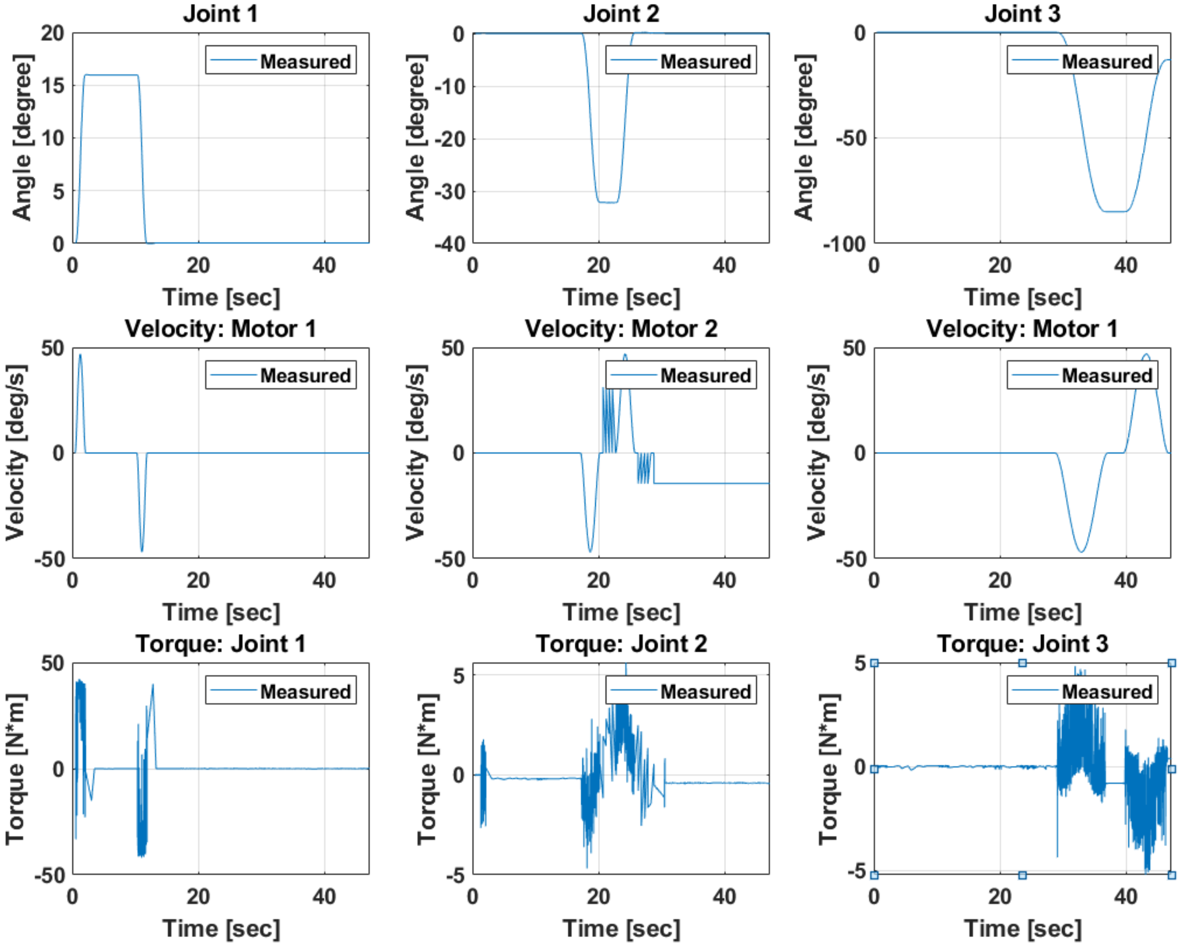

Figure 7-16: DMRbot's joint angles, velocities, and torques, during RT Telerehabilitation Exercise mode using individual joint control of the robot to provide PRE

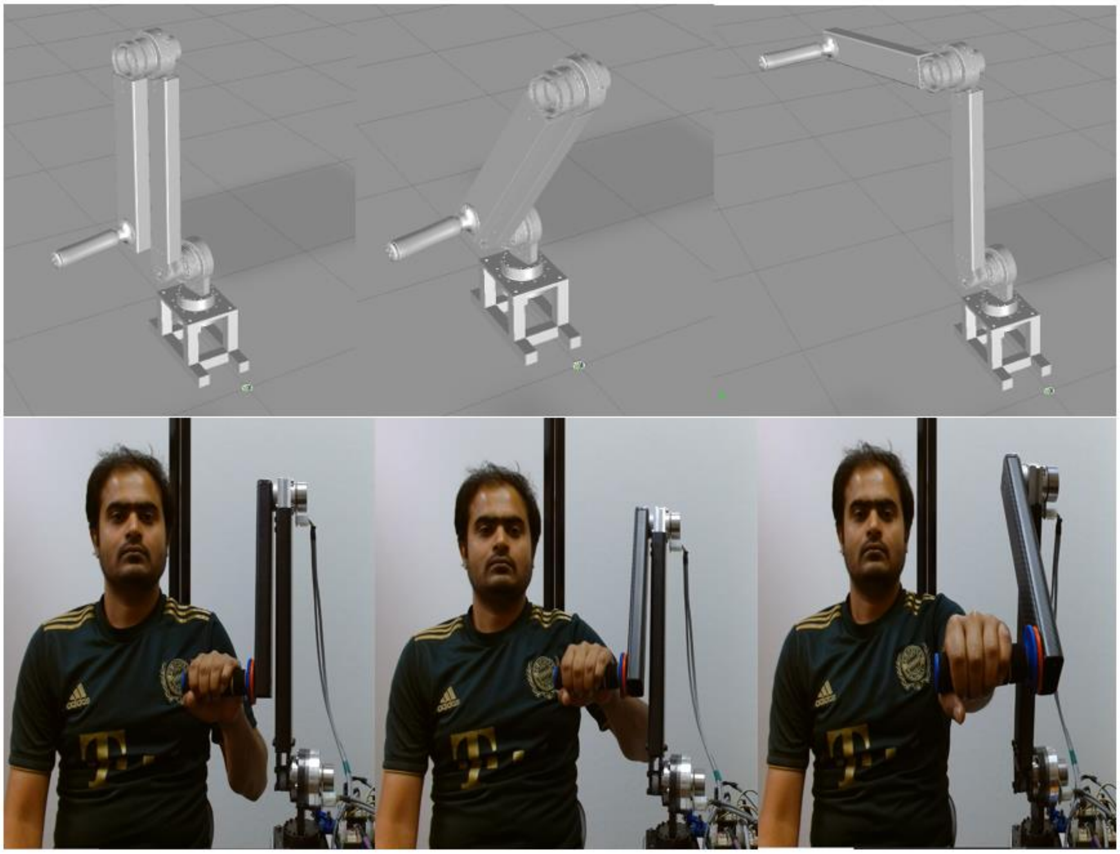

Figure 7-17: Monitoring RT control of the robot to provide PRE through the Vuforia Studio AR platform and observing participant's upper-limb movement through Microsoft Teams video session.

Like the previous exercise, during the experiment with subject-B, the robot started its motion from its Zero position (all joints are set to zero angles). Figure 7-18 and Figure 7-19 show the results from the recorded experiment data for joint based PRE experiment. To do this exercise, the operator manipulates the robot joints in the following ways:

During the Slider-based control, the robot's joints are moved as follows:

- Joint-1 stays in its initial position (0o) for around 25 seconds and then moves from in its initial position (0o) to 20°, -8°, 18°, and 2° for the rest of the trajectory;

- Joint-2 moves continuously from its initial position (-1.3°) to –0.4°for about 52 sec, and then it ends at -1.1°;
- Joint-3 moves from its initial position (0°) to 120°, 50°, and 80° respectively for approximately 42 sec, and then it ends at 48°;

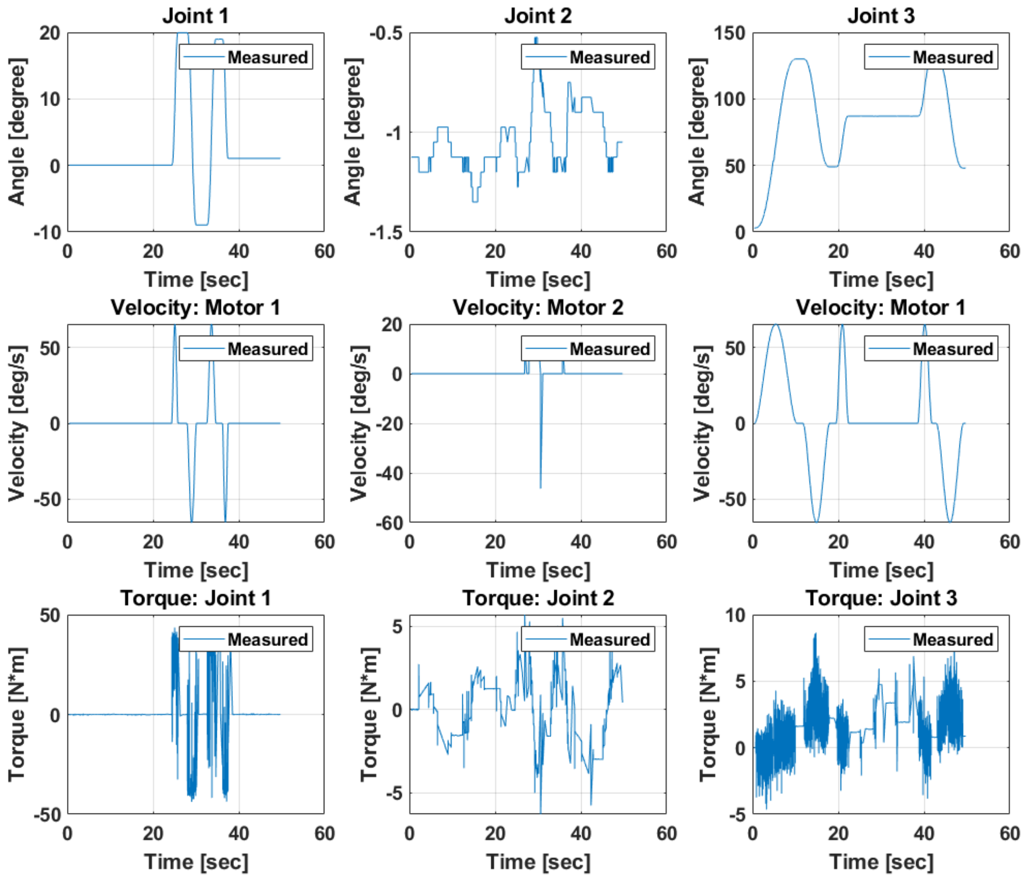

Figure 7-18 DMRbot's joint angles, velocities, and torques, during RT Telerehabilitation Exercise mode using individual joint control of the robot to provide PRE

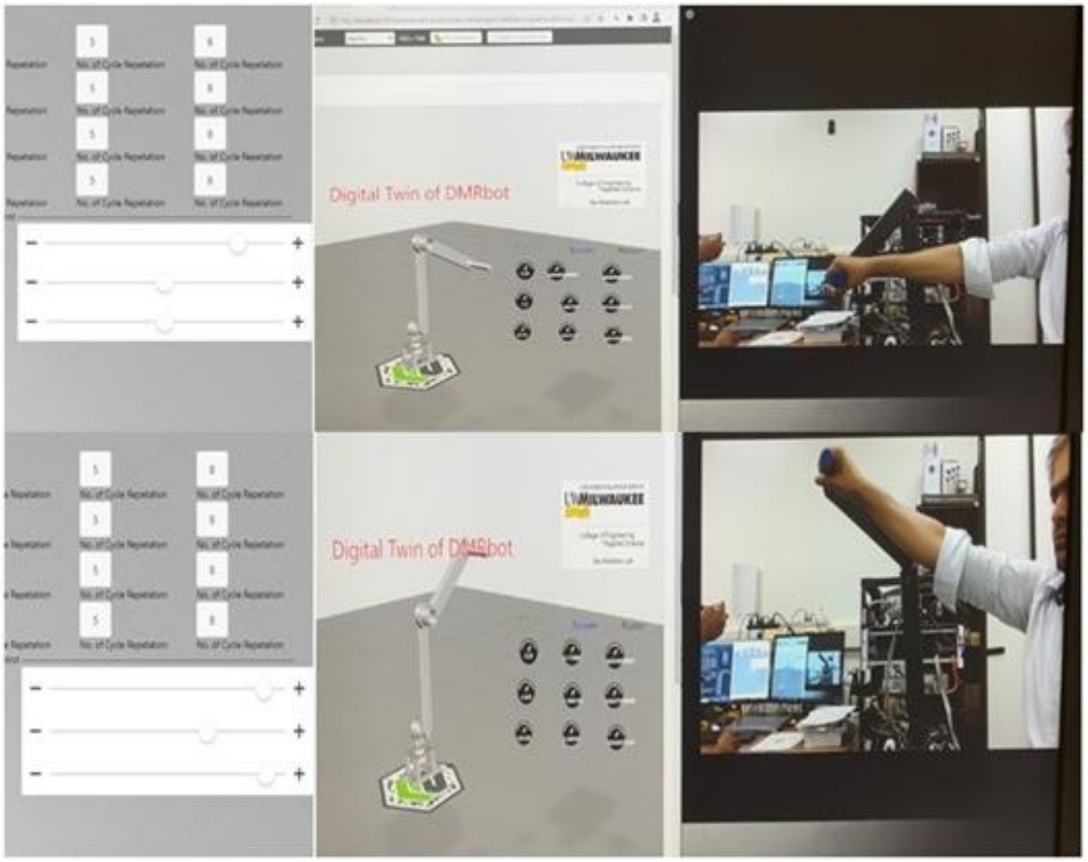

Figure 7-19 Monitoring RT control of the robot to provide PRE through Vuforia Studio AR platform and observing participant's upper-limb movement through Microsoft Teams video session.

7.3 Interactive Real-Time (RT) Control using Joystick to Provide PRE for TRE

In this interactive RT exercise mode, the DMRbot's end-effector is controlled using a Logitech joystick. The control technique for remotely operating the DMRbot using a Logitech joystick is described in Section 6.5. To provide this exercise, the operator/therapist uses the joystick to remotely manipulate the robot's end-effector position at a specific distance depending on the subject's upper-limb range of motion and observes the changes on the AR digital twin. The activities will then be tracked using an augmented reality digital twin of the robot.

Like previous exercises, during the experiment (as shown in *Figure 7-2*), the participants seated on the chair held the robot's end-effector (handle) while facing the MS Teams' call screen mode. The therapist/operator operates the joystick to control the robot's end-effector position. As illustrated in *Figure 7-1*, the operator used the remote joystick to move the robot's end-effector from its starting positions of X = 190 mm, Y = 200 mm, and Z = 180 mm. Figure 7-20 depicts the DMRbot's joint angles, velocities, and torque. Figure 7-21 depicts the AR digital twin of the DMRbot robot with end-effector position and participant upper-limb movement during the RT telerehabilitation exercise, controlling DMRbot’s end-effector position.

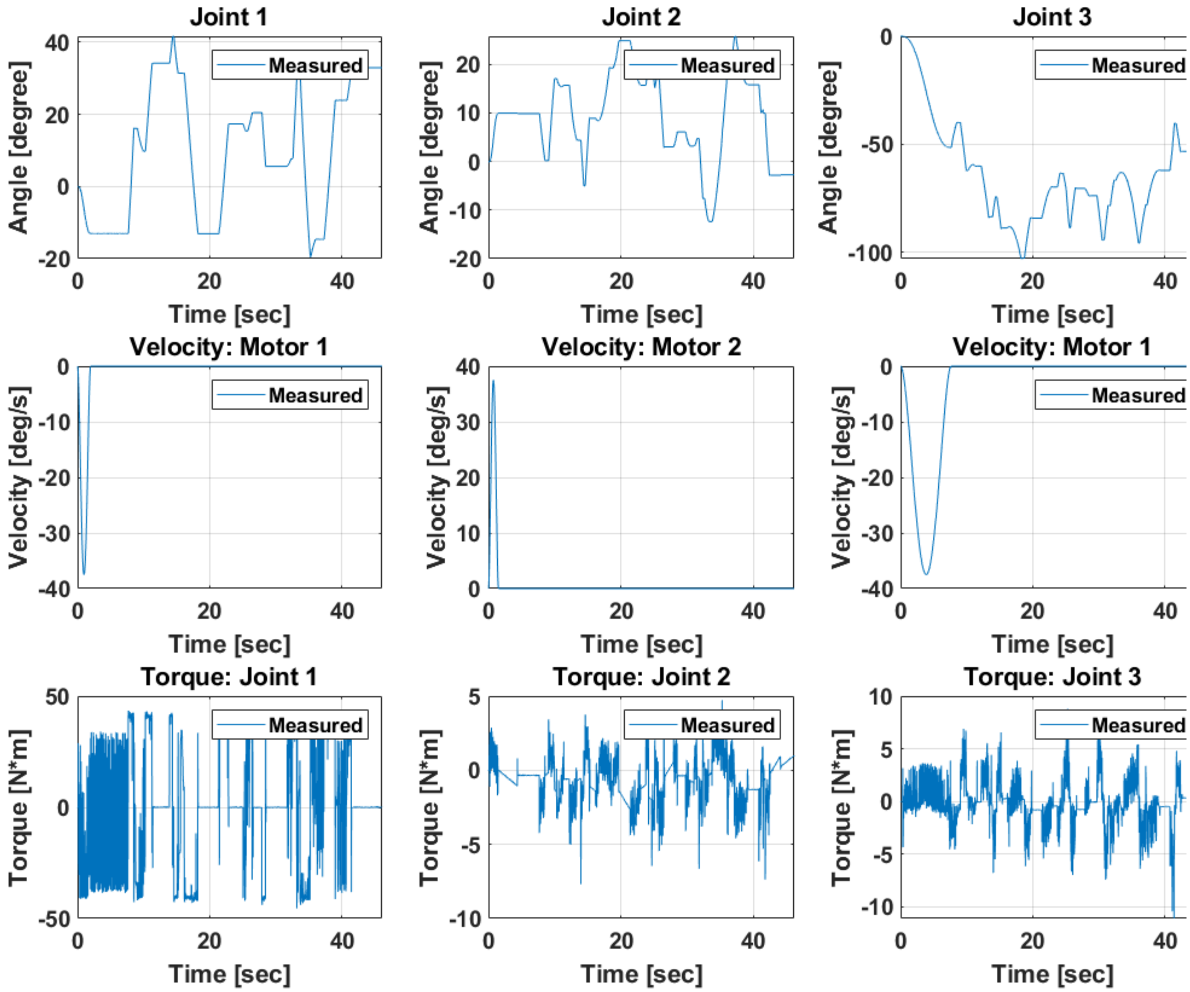

Figure 7-20: DMRbot's joint angles, velocities, and torques during RT control using a joystick to provide PRE.

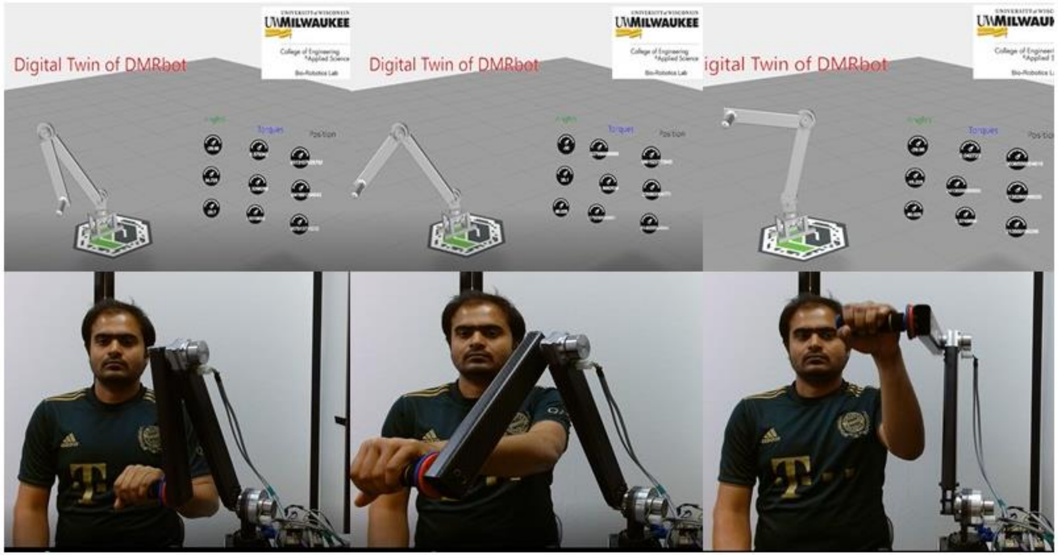

Figure 7-21: Monitoring RT control mode using a joystick to provide PRE through Vuforia Studio AR platform and observe end-effector position and participant's upper-limb movement through Microsoft Teams video session.

The experimental results with subject-B are shown in Figure 7-22 and Figure 7-23, Figure 7-22 depicts the DMRbot's joint angles, velocities, and torque. And Figure 7-23 illustrates the AR digital twin of the DMRbot robot with end-effector position and participant upper-limb movement during the RT telerehabilitation exercise, controlling DMRbot's end-effector position.

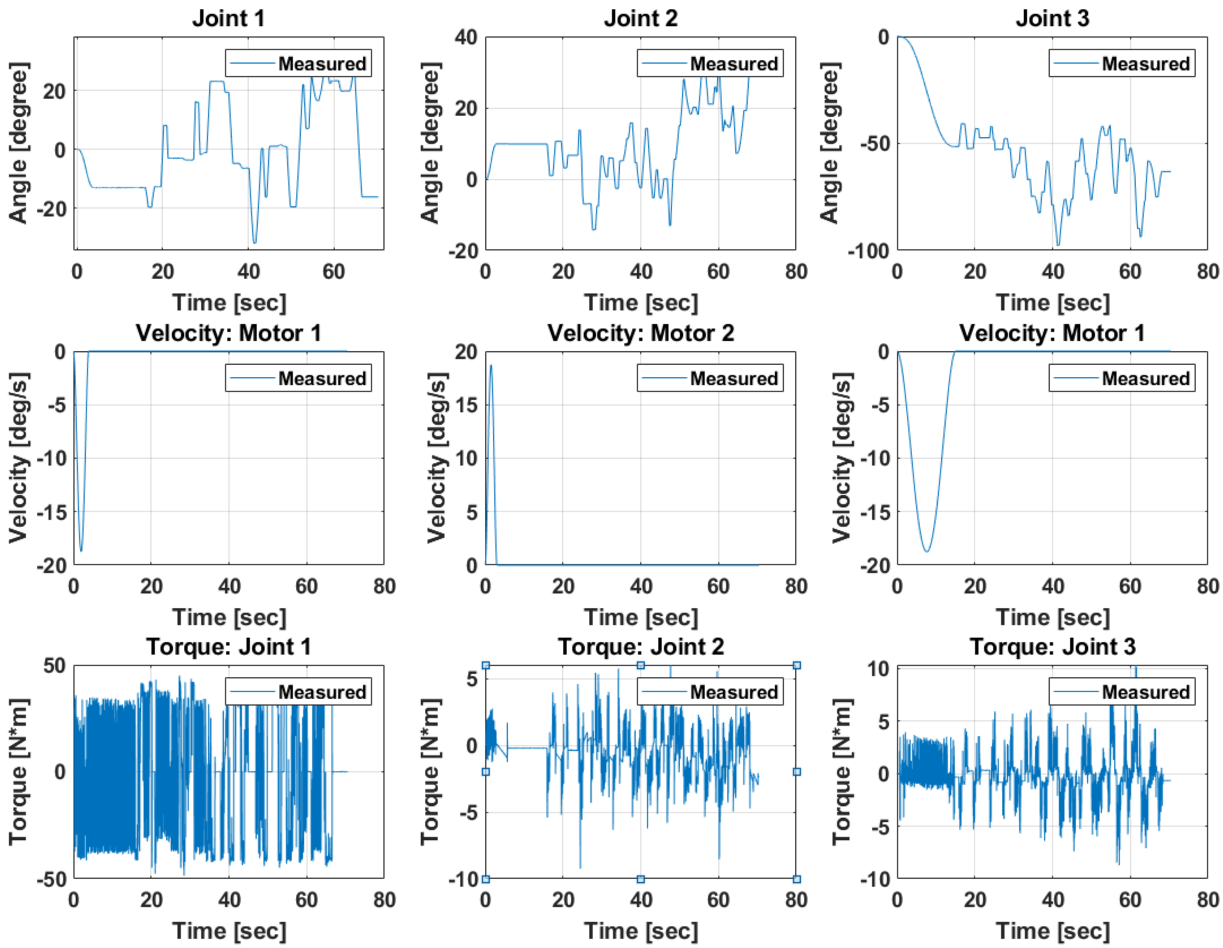

Figure 7-22 DMRbot's joint angles, velocities, and torques during RT control using a joystick to provide PRE.

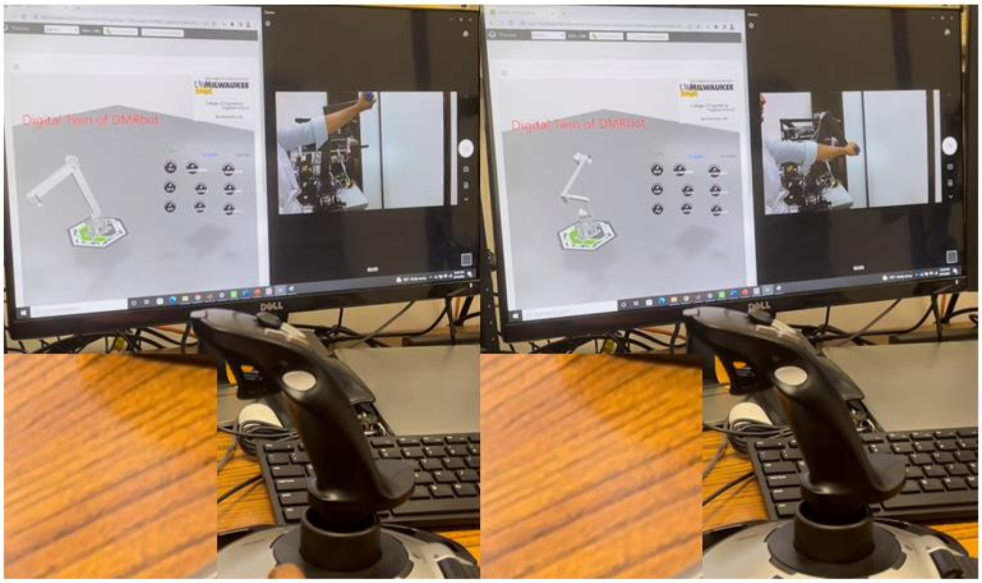

Figure 7-23 Monitoring RT control mode using a joystick to provide PRE through Vuforia Studio AR platform and observe end-effector position and participant's upper-limb movement through Microsoft Teams video session.

The proposed IIoT and augmented reality-based framework promises a stable control system for home-based telerehabilitation, but the framework should have a continuous and stable connection. The system becomes inoperable unstable if the connection is lost and can't be used. From the experimental results shown in Figure 7-6 to Figure 7-23 it is clear that the IIoT and augmented reality-based framework can be used to teleoperate an end-effector type desktop mounted robot to provide arm movement exercises.

Chapter 8

CONCLUSIONS AND FUTURE WORK

Conclusion

In this study, we developed a minimal viable product 3 DoF end-effector rehabilitation robot to provide various passive telerehabilitation exercises to persons with upper limb impairment.

PTC's Industrial Internet of Things (IIoT) platform is utilized to remotely provide home-based rehabilitation therapy with the developed robot to persons with upper limb dysfunctions. Remote rehabilitation is feasible because of the low latency (accelerated by ThingWorx's cloud services deployment) and robust connection topology. Furthermore, this research uses of the digital twin structure, made possible by the Vuforia studio application, to see accurate robot movements occurring in remote locations. The experimental results indicated that the proposed IIoT and augmented reality-based framework for human-robot communication can be utilized for various telerehabilitation applications for a home setup.

Post-stroke patients with upper limb disabilities need long-term therapist help for rehabilitation, which usually takes place in a hospital or outpatient clinic. Travel and transportation are important barriers to patients obtaining proper treatment, often resulting in long-term impairment and the need for home-based rehabilitation devices that can deliver rehabilitation therapy at the user's convenience. Because of the COVID-19 pandemic, all patients with disabilities have difficulty completing their physical therapy due to social distance-imposed access limits to suitable rehabilitation facilities and services. Telerehabilitation has the potential to address this problem. We developed a minimal viable product 3 DoF end-effector rehabilitation robot in this study to provide various passive telerehabilitation exercises to persons with upper limb impairment. The

proposed framework was built using many 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.

Future Works

Future studies will include developing a control method and VR/MR game environments to provide active-assisted rehabilitative therapy using DMRbot. We will use Microsoft HoloLens 2 for this purpose. The Azure mixed reality services will extract and display digital data for telerehabilitation, while the Microsoft HoloLens 2 mixed reality platform will be used to exhibit digital materials on holographic displays.

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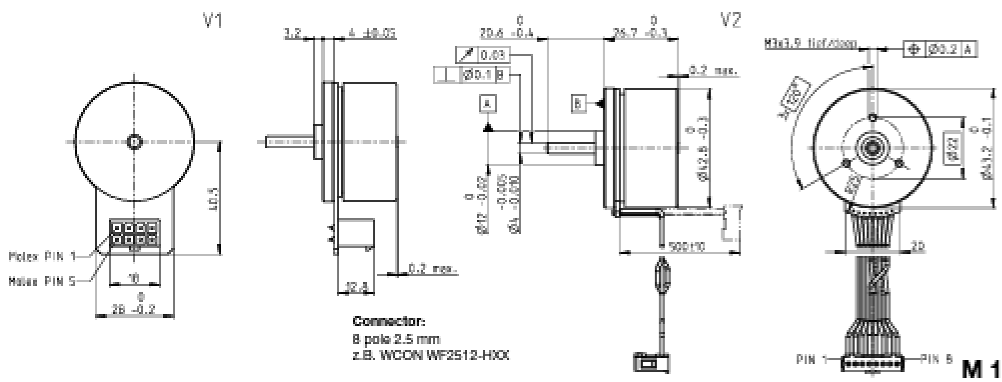
APPENDIX – A

maxon flat motor

EC 45 flat ∅42.8 mm, brushless, 70 Watt



M 1:2

Stock program
Standard program
Special program (on request)

Part Numbers				
V1 with Hall sensors	397172	402685	402686	402687
V2 with Hall sensors and cables	411812	411814	411815	411816
Motor Data (provisional)				
Values at nominal voltage				
1 Nominal voltage V	24	30	36	48
2 No load speed rpm	6110	6230	6330	3440
3 No load current mA	234	194	166	48.1
4 Nominal speed rpm	4860	4990	5080	2540
5 Nominal torque (max. continuous torque) mNm	128	112	108	134
6 Nominal current (max. continuous current) A	3.21	2.36	1.93	0.936
7 Stall torque[1] mNm	1460	1170	1100	915
8 Stall current A	39.5	25.8	20.7	6.97
9 Max. efficiency %	85	84	83	84
Characteristics				
10 Terminal resistance phase to phase Ω	0.608	1.16	1.74	6.89
11 Terminal inductance phase to phase mH	0.463	0.691	0.966	5.85
12 Torque constant mNm / A	36.9	45.1	53.3	131
13 Speed constant rpm / V	259	212	179	72.7
14 Speed / torque gradient rpm / mNm	4.26	5.44	5.85	3.82
15 Mechanical time constant ms	8.07	10.3	11.1	7.24
16 Rotor inertia gcm²	181	181	181	181

Specifications

Thermal data

17	Thermal resistance housing-ambient	3.56 K/W
18	Thermal resistance winding-housing	4.1 K/W
19	Thermal time constant winding	29.6 s
20	Thermal time constant motor	178 s
21	Ambient temperature	-40 ... +100°C
22	Max. winding temperature	+125°C

Mechanical data (preloaded ball bearings)

23	Max. speed	10000 rpm
24	Axial play at axial load < 4.0 N	0 mm
	> 4.0 N	0.14 mm
25	Radial play	preloaded
26	Max. axial load (dynamic)	3.8 N
27	Max. force for press fits (static)	50 N
	(static, shaft supported)	1000 N
28	Max. radial load, 5 mm from flange	21 N

Other specifications

29	Number of pole pairs	8
30	Number of phases	3
31	Weight of motor	141 g

Values listed in the table are nominal.

Connection	V1	V2 (AWG 24)
Pin 1	Hall sensor 1*	Motor winding 1
Pin 2	Hall sensor 2*	Motor winding 2
Pin 3	V_{Hall} 4.5 ... 18 VDC	Motor winding 3
Pin 4	Motor winding 3	V_{Hall} 4.5 ... 18 VDC
Pin 5	Hall sensor 3*	GND
Pin 6	GND	Hall sensor 1*
Pin 7	Motor winding 1	Hall sensor 2*
Pin 8	Motor winding 2	Hall sensor 3*

*Internal pull-up (7 ... 13 kΩ) on V_{Hall}

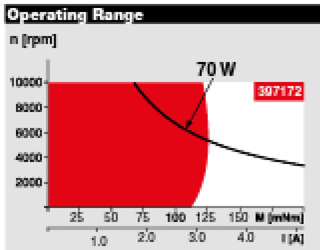
Wiring diagram for Hall sensors see p. 47

Cable for V1

Connection cable Universal, L = 500 mm **339380**

Connection cable to EPOS, L = 500 mm **354045**

Operating Range



Comments

Continuous operation
In observation of above listed thermal resistance (lines 17 and 18) the maximum permissible winding temperature will be reached during continuous operation at 25°C ambient.
= Thermal limit.

Short term operation
The motor may be briefly overloaded (recurring).

Assigned power rating

maxon Modular System

Details on catalog page 36

Planetary Gearhead
∅42 mm
3 - 15 Nm
Page 363

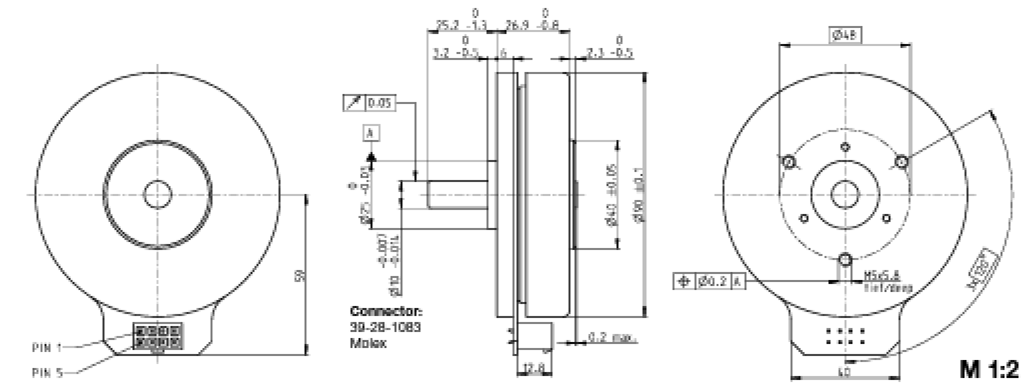
Spur Gearhead
∅45 mm
0.5 - 2.0 Nm
Page 365

Encoder MILE
256 - 2048 CPT,
2 channels
Page 412

Recommended Electronics:

Notes	Page 36
ESCON 36/3 EC	455
ESCON Mod. 50/4 EC-S	455
ESCON Module 50/5	455
ESCON 50/5	457
DEC Module 50/5	459
EPOS4 50/5	463
EPOS4 Mod./Comp. 50/5	463
EPOS2 P 24/5	470
MAXPOS 50/5	473

EC 90 flat ∅90 mm, brushless, 90 Watt



- Stock program
- Standard program
- Special program (on request)

Part Numbers

		with Hall sensors	323772	429271	244879
Motor Data					
	Values at nominal voltage				
1	Nominal voltage	V	24	36	48
2	No load speed	rpm	3190	3120	2080
3	No load current	mA	544	348	135
4	Nominal speed	rpm	2590	2510	1610
5	Nominal torque (max. continuous torque)	mNm	444	580	533
6	Nominal current (max. continuous current)	A	6.06	4.76	2.27
7	Stall torque	mNm	4940	7480	4570
8	Stall current	A	70	69	21.1
9	Max. efficiency	%	84	87	85
	Characteristics				
10	Terminal resistance phase to phase	Ω	0.343	0.522	2.28
11	Terminal inductance phase to phase	mH	0.264	0.625	2.5
12	Torque constant	mNm/A	70.5	109	217
13	Speed constant	rpm/V	135	88	44
14	Speed/torque gradient	rpm/mNm	0.659	0.423	0.462
15	Mechanical time constant	ms	21.1	13.6	14.8
16	Rotor inertia	gcm^2	3060	3060	3060

Specifications

Thermal data

17	Thermal resistance housing-ambient	1.91 K/W
18	Thermal resistance winding-housing	2.6 K/W
19	Thermal time constant winding	46 s
20	Thermal time constant motor	283 s
21	Ambient temperature	-40...+100°C
22	Max. winding temperature	+125°C

Mechanical data (preloaded ball bearings)

23	Max. speed	5000 rpm
24	Axial play at axial load < 15 N	0 mm
	> 15 N	0.14 mm
25	Radial play	preloaded
26	Max. axial load (dynamic)	12 N
27	Max. force for press fits (static)	183 N
	(static, shaft supported)	8000 N
28	Max. radial load, 5 mm from flange	68 N

Other specifications

29	Number of pole pairs	12
30	Number of phases	3
31	Weight of motor	600 g

Values listed in the table are nominal.

Connection

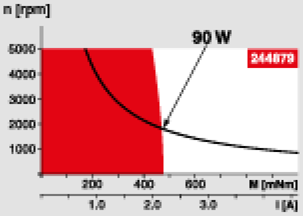
Pin 1	Hall sensor 1
Pin 2	Hall sensor 2
Pin 3	V_{Hall} 4.5...18 VDC
Pin 4	Motor winding 3
Pin 5	Hall sensor 3
Pin 6	GND
Pin 7	Motor winding 1
Pin 8	Motor winding 2

Wiring diagram for Hall sensors see p. 43

Cable

Connection cable Universal, L = 500 mm	**339380**
Connection cable to EPOS2, L = 500 mm	**354045**

Operating Range



Comments

Continuous operation
In observation of above listed thermal resistance (lines 17 and 18) the maximum permissible winding temperature will be reached during continuous operation at 25°C ambient.
= Thermal limit.

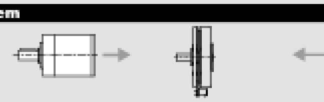
Short term operation
The motor may be briefly overloaded (recurring).

Assigned power rating

maxon Modular System

Overview on page 28–36

Planetary Gearhead
∅52 mm
4 - 30 Nm
Page 351



Encoder MILE
512 - 6400 CPT,
2 channels
Page 390

Recommended Electronics:

Notes	Page **32**
ESCON Mod. 50/4 EC-S	427
ESCON Mod. 50/5	427
ESCON 50/5	428
ESCON 70/10	428
DEC Module 50/5	430
EPOS2 24/5, 50/5, 70/10	435
EPOS2 P 24/5	438
EPOS4 Module/CB 50/5	442
EPOS4 Module 50/8	443
EPOS4 Comp. 50/8 CAN	443
MAXPOS 50/5	447

APPENDIX – B