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RESEARCH ARTICLE

A New System for the Remote Configuration and Monitoring of VR Rehabilitation Exercises

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ABSTRACT Virtual reality (VR) and head-mounted displays (HMDs) are gaining popularity in rehabilitation. However, to be effectively integrated into clinical settings, these systems must offer advanced features such as telerehabilitation support, flexible rehabilitator-patient ratios, and real-time monitoring and interaction with virtual scenarios. To meet these requirements, this paper proposes a new system for the remote configuration and monitoring of VR-HMD rehabilitation exercises, enabling experts to interact with and manage patient-specific virtual scenarios. The system comprises two executables: one on the VR-HMD and another on an external monitoring device controlled by the expert, both coordinated by a shared Network Manager library. The paper evaluates the system by assessing time overhead (the duration when the patient is not actively engaged in rehabilitation) and system performance (including frames per second, network bandwidth usage, and monitoring effectiveness). This evaluation is compared with traditional HMD rehabilitation setups that lack rehabilitator interaction. Additionally, the system is reviewed in terms of development effort (steps and time required to adapt exercises for each monitoring method) and developers' feedback on usability, functionality, ease of use, and future interest. Evaluation results indicate that the proposed system significantly reduces time overhead—by up to 85%—by minimizing the need to transfer the HMD between patient and rehabilitator. The system maintains performance with only a 2-5% decrease and limits network usage to under 350 kilobytes per second, ensuring fast and accurate monitoring. Developers have rated the system highly for usability and functionality, though ease of use needs improvement, and future interest depends on more streamlined development features and better documentation. Overall, the system enhances VR rehabilitation by facilitating seamless intervention, efficient monitoring, and device compatibility through low-bandwidth solutions and adjustable visual quality, thus improving control, interaction, and effectiveness.

INDEX TERMS Virtual reality, rehabilitation, networking.

I. INTRODUCTION

In recent years, the development and use of commercial and custom-made virtual reality training (VRT) systems for rehabilitation purposes have increased significantly [1], [2], [3], [4]. Evidence demonstrates that these applications improve motivation, adherence, and training dose among patients [5], [6], [7], [8], resulting in improvement in patient recovery [9], [10]. Generally, the VRT systems have been customized to target specific patients' disabilities including reduced motor function, mobility, postural control, or cognitive impairments, among others [10], [11]. Recently, VR head-mounted displays (HMD) have become one of the key components of these environments. These devices equipped with multiple built-in cameras can track user movements allowing them to naturally interact with the objects of the virtual environment [12]. As a result, patients are immersed in safe, controlled, and engaging virtual worlds where rehabilitation tasks can be carried out [13], [14], [15].

Behind VRT systems there is a design and development process where multidisciplinary teams with knowledge on technology, rehabilitation, and domain content

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collaborate [16]. From a technological point of view, during design, it is necessary to know: (1) the rehabilitation exercises that have to be carried out; (2) the virtual context where the exercises will be conducted; (3) the rehabilitation objectives to be reached by the patient; (4) the assessment strategy that will evaluate patient progress and (5) the rehabilitation strategy that, considering pedagogical models and feedback strategies, defines the sequence and organization of the rehabilitation content for the patient to achieve the objectives. In addition, critical elements such as the development tools, the hardware that must be supported, or the required level of desired immersion need to be taken into account. All the necessary knowledge, the diversity of involved profiles in the creation process, and the diversity of patients make the VRT design and development process challenging [17], [18].

Moreover, once a final product is obtained there is a deployment phase which is also challenging due to the diversity of scenarios that can be given. These differ according to factors such as the patient-rehabilitator placement which can be the same (rehabilitation) or at different places (telerehabilitation); the rehabilitator-patient ratio which can be one-to-one or one-to-more; and the rehabilitator-virtual scenario interaction which can only see the patient performance or see and also interact with the virtual scene. This last situation is of special interest since it allows the rehabilitator to guide and help the patient if it is necessary leading to more fluent rehabilitation sessions. It is crucial for the rehabilitator to observe how the patient performs in the virtual scenario, as this allows for the early detection of potential issues and enables prompt intervention, and also to interact when necessary. By closely monitoring the patient's interactions and responses within the virtual environment, the rehabilitator can identify any difficulties or deviations from the expected progress. Remote control serves as the optimal solution for this, allowing the rehabilitator to follow the patient's execution in real-time and make necessary adjustments immediately. This ensures that problems are promptly addressed, maintaining the continuity and effectiveness of the rehabilitation process without disrupting its flow.

Three approaches can be considered to enable the necessary interaction capabilities between rehabilitators and virtual scenarios. The first approach uses the off-the-shelf libraries provided by the device, leveraging their built-in functionalities. However, a significant limitation of this strategy is that current implementations often restrict rehabilitators to merely observing the patient's actions within the virtual scenario, without the capability to interact directly with the virtual models. This limitation becomes particularly evident when assistance is required, as the rehabilitator may need to physically remove the head-mounted display to provide guidance or intervention [19]. Note also that this approach is not feasible in telerehabilitation scenarios, where the rehabilitator and patient are geographically separated, making physical interaction impossible.

The second approach implements strategies inspired by multiplayer games, where both the rehabilitator and patient wear HMDs to interact within the same virtual space [20]. This approach is feasible in telerehabilitation scenarios [21]. However, a critical challenge arises from this setup since the rehabilitator must remain in the physical space to oversee the patient's performance comprehensively and to manage any potential discomfort or side effects that may arise from prolonged VR exposure. Additionally, it is common for rehabilitators to need to supervise multiple patients simultaneously, a task that becomes impractical with this approach due to the need for physical presence and direct oversight in each VR session.

The third approach involves developing a custom solution, which entails the complete design and development process tailored specifically to the identified needs [22], [23]. While this strategy demands significant effort in planning, coding, and testing, it offers the distinct advantage of creating an implementation that precisely meets the requirements of the rehabilitation environment. By customizing the solution, developers can integrate functionalities that may not be readily available in off-the-shelf or game-inspired approaches. Note that this approach ensures that the VR rehabilitation system aligns perfectly with the identified challenges and objectives, optimizing the interaction between rehabilitators and patients and the overall effectiveness of the rehabilitation process.

Regarding developing a custom solution, it is crucial to address existing gaps in the application of remote control within VR environments. Current research predominantly focuses on patient outcomes in VR rather than on the technological aspects and challenges associated with implementing remote control. There is a noticeable absence of detailed studies that delve into technical requirements such as latency, reliability, and user interface design, all essential for effective remote control in VR rehabilitation scenarios. Additionally, there is limited literature exploring the broader implications of integrating remote control technology, including infrastructure requirements, training for rehabilitators, and the necessary resources for seamless operation.

Moreover, from a technological point of view, the system must enable experts to deliver optimal treatment to patients while ensuring comprehensive interaction capabilities. It must operate reliably under varying rehabilitation conditions, accommodating challenges such as slow internet connections or crowded Wi-Fi networks. In this context, two critical challenges will be specifically addressed:

- Connectivity with limited internet access: The effectiveness of remote VR therapy depends on the expert's ability to interact with the patient and the virtual environment in real time. A reliable internet connection is essential for seamless communication. However, the substantial amount of data in a VR environment can strain communication, causing delays, data loss, or dropped connections. These issues can degrade the

experience for both the expert monitoring the patient and the patient undergoing rehabilitation, impacting feedback delivery and task performance. Consequently, this may lead to frustration, loss of motivation, and ultimately compromise the effectiveness of therapy sessions.
- Limited Environmental Control: Therapists often need to manipulate the virtual environment during sessions to interact with objects, adjust difficulty levels, or introduce new challenges tailored to the patient's progress. Current remote control systems have limitations in this regard, which hinders therapists' ability to personalize the VR experience and optimize treatment outcomes.

To address these challenges, two main contributions will be presented:

- An optimized network infrastructure that minimizes bandwidth usage and ensures a seamless VR experience.
- Intuitive and feature-rich remote control interfaces that provide therapists with greater control over the virtual environment for a more personalized and effective treatment approach.

By resolving these challenges and hence reducing the barrier of collaboration, better opportunities for treatment both in rehabilitation centers and at home through telerehabilitation are expected. Unlike traditional approaches where all participants require VR devices to interact, our approach allows asymmetric interaction using non-immersive devices.

The aim of the paper is to present the design and development details of a new system specifically designed to remotely control and supervise HMD-based rehabilitation performance, allowing the rehabilitator's control and interaction with the virtual scenario. The tests carried out in real scenarios to demonstrate the system's advantages with respect to classical approaches will be also presented. It is expected the paper can serve as a guide for technicians interested in the application of these solutions, providing practical insights and detailed implementation strategies.

Besides this introduction, the paper has been structured as follows. In Section II, Related Work is presented. In Section III the design and development process is described. Then, in Section IV, the evaluation of the system is given and discussed. Finally, Conclusions and Future Work are presented in Section V.

II. RELATED WORK

Advances in technology and the reduction of their costs have led to great changes in rehabilitation environments. As examples consider Chuang et al. who conducted a network meta-analysis comparing exergame and virtual reality (VR) assisted rehabilitation to conventional methods for Parkinson's disease, highlighting benefits [24]; Segear et al. who explored visual feedback and guided balance training in immersive VR for lower extremity rehabilitation [25]; Bargeri et al. who reviewed systematic reviews on VR rehabilitation post-stroke, emphasizing its efficacy [26]; Xiao et al. who compared VR technology and computer-assisted cognitive rehabilitation for post-stroke cognitive impairment [27]; or Amin et al. who assessed advanced technologies including VR for stroke recovery [28]. These studies collectively illustrate the evolving landscape of rehabilitation technologies, showcasing VR's potential across different neurological conditions and emphasizing its role in enhancing therapeutic outcomes.

Among technological advances, HMD-based therapies have increased their popularity thanks to their immersion capacity. From a technical point of view, HMD devices achieve immersion by using a hardware tracking device that couples the user's head movements with the virtual environment. By moving the head, the user can choose what to look at in the virtual scenario achieving a greater level of autonomous interaction. In this regard, as reference devices consider the Meta Quest 2 [29], an immersive all-in-one VR headset that delivers a premium VR experience without the need for a separate gaming PC or console; VIVE [30], which offers a range of VR headsets, games, and metaverse experiences; OSVR [31], an open-source VR platform that enables developers to create VR applications; or the Valve Index [32], a high-end VR headset designed for PC gaming, featuring advanced controllers and tracking technology.

Different studies have demonstrated that rehabilitation outcomes improve with HDM-assisted rehabilitation therapies. See for instance, Khan et al. who reviewed the use of VR in post-stroke neurorehabilitation, finding it is associated with improved functional outcomes [33] or Sokołowska [34] who examined the impact of VR cognitive and motor exercises on brain health. There are also different systematic reviews on the topic such as Demeco et al. who focused on the use of immersive VR in post-stroke rehabilitation [35] emphasizing the importance of patient engagement and highlighted the challenges faced by both patients and rehabilitators in adapting to these technologies; Amini Gougeh and Falk who presented a systematic review on the use of HMD-based VR and physiological computing for stroke rehabilitation, examining technological aspects, biosignal applications, and clinical outcomes [36]; or Palacios-Navarro and Hogan who performed a systematic review and meta-analysis on HMD-based therapies for post-stroke adults, assessing their effectiveness in improving motor function and activities of daily living [37].

Centering on the performance of these HDM-assisted rehabilitation systems, patient recovery, and user experience have been the main focus of interest of carried out studies. These studies commonly used metrics that consider parameters such as the patient's motor function measured using medical scale methods including Brunnstrom's foundational work on motor testing procedures in hemiplegia, which established a sequential approach to understanding recovery stages and remains critical for developing effective rehabilitation protocols [38]; the Motor Assessment Scale introduced by Carr et al., which provided a comprehensive tool for evaluating the motor functions of stroke patients and remains widely used in clinical settings [39]; or the detailed method for assessing motor recovery in post-stroke patients offered by the Fugl-Meyer (FM) assessment scale, which has been instrumental in both clinical practice and research [40]. The user experience is also of great interest, and metrics to evaluate usability and comfort aspects such as sickness effect, heart rate, body sway, skin conductance, etc. are applied. Laessoe et al., investigated motion sickness and cybersickness caused by sensory mismatch in VR environments, a significant consideration for ensuring patient comfort and compliance during therapy sessions [41]. Martirosov et al., investigated cybersickness across different levels of VR immersion, providing insights into how varying degrees of immersion can impact patient experience and therapy outcomes [42]. From a technological point of view, aspects related to the quality of virtual scenarios, the achieved degree of immersion, or the tracking precision, among others, are also centers of interest. Torres Vega et al. discussed the technological advancements necessary for creating immersive interconnected virtual and augmented reality systems, highlighting the role of 5G and IoT in enhancing the quality and effectiveness of these rehabilitation technologies [43].

Note that although rehabilitators are essential in HDM-based rehabilitation scenarios, their main role has often been overlooked in favor of focusing on patients and technological advancements. In this regard, Levac et al. emphasized the critical role of therapists in VR-based stroke rehabilitation, advocating for the integration of motor learning strategies to enhance patient outcomes [44]. Segal et al. provided insights into therapists' perceptions of the benefits and challenges associated with VR treatments, highlighting practical considerations and potential barriers to adoption [45]. Similarly, Schwartzman et al. explored why some therapists do not currently incorporate VR technology into clinical practice, shedding light on factors that influence its uptake [46]. These studies collectively underscore the need to better understand and support therapists in leveraging HDM technologies effectively, ensuring they are equipped with the necessary skills and resources to optimize rehabilitation outcomes.

Additionally, from a practical point of view, in most cases, it has been assumed that rehabilitators are technically skilled enough to apply proposed solutions and less attention has been given to their needs. This has been a limiting factor in exploiting the advantages of designed approaches. For example, imagine a patient performing a rehabilitation exercise with a HMD. Typically, control of the exercise is given to the patient, while the rehabilitation provider monitors progress on an additional screen displaying the virtual scene and the patient's performance. However, this visual oversight is sometimes insufficient, as various issues can disrupt the rehabilitation process and require the rehabilitator's intervention. These include situations where the patient is improperly positioned within the play area, causing objectives to be out of reach or objects to become inaccessible due to incorrect placement. Another situation arise when the patient misunderstands instructions and requires visual clarification, or when technological errors occur. In these cases, the rehabilitator must remove the VR headset from the patient to resolve these issues, and sometimes they must wear the headset themselves to restart the application or correct the tracking position. Allowing the rehabilitator to interact with scene objects from another device could prevent session interruptions and maintain the patient in a more comfortable state, thereby reducing frustration. This reveals a necessity to develop tools that facilitate the work of the rehabilitators in preparing the exercises, monitoring the rehabilitation sessions, and providing guidance and support without interrupting the immersion. To contribute to a solution to these problems, a new system to facilitate the rehabilitator tasks is proposed. This system will enable them to remotely control and supervise HMD-based rehabilitation performance, allowing for effective interaction and management of the virtual scenario.

III. SYSTEM DESCRIPTION

The proposed system has been designed considering the rehabilitator needs and with the aim of supporting as many HMD rehabilitation scenarios as possible. Figure 1 illustrates the cases that have to be covered which include rehabilitation and telerehabilitation, the possibility for a rehabilitator to control more than one patient simultaneously, and the possibility to visualize and interact with the virtual scene. Moreover, although focused and described considering HMD devices the proposed system could be extended to control patient performance when using other devices such as tablets or smartphones.

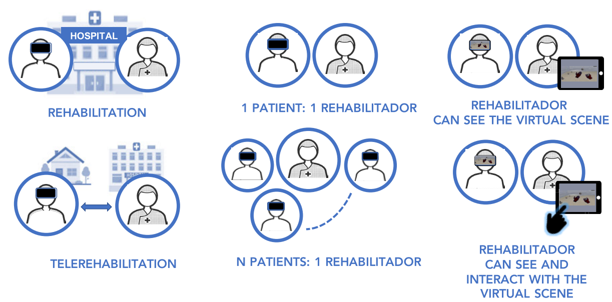

FIGURE 1. The different rehabilitation scenarios that need to be supported by the proposed framework.

To create the system a classical development process where experts and technologists have been working in collaboration has been applied. The process started with a general analysis and requirements gathering, followed by a system design process, coding and testing, and system deployment. All these steps are described in the next.

A. SYSTEM REQUIREMENTS

The system requirements have been defined considering the needs of the rehabilitation team and the two profiles involved in the rehabilitation sessions: (i) the rehabilitation team, composed of doctors, nurses, physiotherapists, etc., and responsible for rehabilitation sessions and (ii) the patients which have to perform the exercises defined by the experts in the context of a rehabilitation session.

1) REHABILITATION SCENARIO

The two key elements of rehabilitation sessions are the rehabilitation exercises and the devices required to carry out the rehabilitation.

- Rehabilitation exercises. These can be described as activities that focus on one or more rehabilitation aspects, such as a certain kind of movement, or focusing attention on a certain part of the brain. The first version of the system will be designed for upper limb motor rehabilitation providing exercises that require the movement of various limbs (hands, arms). Exercises will take place in a virtual room with a table and objects on it, focusing on interactions with other virtual objects through touching, pressing, and grabbing. There will be also different goals for the objects, which may have to be classified (by color, image, or shape), or pressed in a certain order or at certain times. The virtual scenario will also represent the patient's hands which will be tracked during exercise performance. The correct performance will be rewarded in a game mode to encourage patient rehabilitation.
- Supported devices. The patient will be using a standalone wireless VR Headset, to allow for full mobility. The experts often handle multiple patients at the same time, with different needs, which may or may not be using VR Headsets. Because of this, the experts cannot be using a VR Headset themselves, as they would have to be putting it on and removing it too often. This means that it is preferred for the expert to be using a traditional non-immersive device, such as a computer, laptop, or tablet. Therefore, the system will have two different interfaces targeting different technologies, the one running on the expert's computer or tablet (the Monitoring Device), denoted *the Expert Interface*, and the other one running on the VR Headset, denoted *the Patient Interface*.

  Since the two interfaces will run on separate devices, it will be necessary for the devices to have network connectivity. For local rehabilitation, only a local Wi-Fi Access Point will be needed. In the case of telerehabilitation, internet connectivity will be required since the two devices will not be in the same local network.

  On top of that, the rehabilitation process will need to be monitored in real-time, and the patient and the expert will need to be able to speak and hear each other. Some VR Headsets and tablet/computer devices have integrated speakers and microphones, but others do not, and an external microphone and speaker/headphone will need to be connected to the computer in those cases.

2) FUNCTIONAL REQUIREMENTS

Once the rehabilitation scenario has been presented, the functional requirements can be set. For the sake of clarity, these have been grouped into four blocks corresponding to the main phases of a rehabilitation session and assuming that there is a list of rehabilitation exercises that has been previously created. The patient and expert have the corresponding devices and there is network connectivity between them.

- System Set-up. In order to allow the communication, the VR Headset and the Expert Interface need to be aware of each other. For ease of use, in local rehabilitation the Expert Interface will be able to initiate the set-up steps, as it is less cumbersome to interact with a complex User Interface using a keyboard or touchscreen. The set-up process will support the following use cases: (i) In the case of telerehabilitation only, register/ unregister a VR headset with the relay server; (ii) Use the Expert Interface to list VR Headsets and choose which one to connect to; (iii) Close the rehabilitation software in the VR Headset; (iv) Disconnect from the VR Headset, allowing the selection of a different headset;
- Session Set-up. Once the Expert Interface is connected, and the patient has put on the VR Headset, the rehabilitator can set up a rehabilitation session. In order to do this, the following use cases will be supported: (i) Choosing the exercises to include in the session, from the list of available exercises; (ii) Choosing how long the session will last; (iii) Choosing difficulty and accessibility parameters for each exercise; (iv) Start the rehabilitation session with the chosen settings.
- Monitoring. While a session is in progress, the rehabilitator needs to ensure the patients are following instructions and performing the correct rehabilitation actions. The use cases that will be supported are: (i) View the virtual world of a patient on the expert interface, including the exercise objects and patient's hands; (ii) Change the point of view used by the expert interface, between the patient's point of view, and a selection of alternative cameras; (iii) In the case of telerehabilitation, it is necessary to be able to have voice communications with the patient, when the rehabilitation cannot be performed in person. During this phase, the patient will be performing the exercises; the goals and gameplay mechanics of these exercises are dependant on the exercise and are not considered here.
- Adjust the exercise conditions. During monitoring, it can be necessary to adjust the rehabilitation and the following use cases will be supported: (i) Change the position and orientation of the patient within the virtual world; (ii) Interact with objects in the virtual world; (iii) Move a physically-enabled object in the virtual world;; (iv) Cancel a session early; (v) Restart an exercise that was in progress; (vi) Skip the current exercise and go to the next one in the queue. These actions

can be performed while the patient is performing the exercises.

3) NON-FUNCTIONAL REQUIREMENTS

The system will be developed using the Unity Engine. It will also support multiple languages. Moreover, it will have a modular design to support the integration of new modules and functionalities in a transparent way for the user. Patient privacy will be ensured by using end to end encrypted communications. In order to ensure reliability and avoid unnecessary disruptions, the system will make use of existing reliable protocols and will perform automatic reconnection in case of loss of connection.

B. ARCHITECTURE

To satisfy all defined requirements the system illustrated in Figure 3 is proposed. This consists of two executables running on different devices, *the VR Interface* inside the VR Headset, and *the Expert Interface* on an external Monitoring Device. In addition, a shared *Network Manager* library is used in both to coordinate the communication protocol. To better present these components it is necessary to first describe the model used to define the rehabilitation exercises, the settings that are used to set-up a rehabilitation session with multiple exercises, and the different phases of the system.

1) EXERCISE MODEL DEFINITION

To define exercises a Unity-based model approach is proposed. The Unity Engine has a *Scene* with *Game Objects* that can have *Components* attached. The *Transform component* defines the position, size, and orientation of an object and it can reference another Transform as the parent in the hierarchy. Object hierarchies can be stored on the program in the form of Prefabs (short for Prefabricated Objects), which can be instantiated later into the Scene. For ease of explanation, the term *Menu* will be used to refer to 2D interfaces shown on top of the 3D environments for the purposes of indication and control. These Menus are also defined using Game Objects and Components.

The rehabilitation exercises are defined ahead of time using this model, with some additional components to assign Object identifiers (IDs) to objects that need to be synchronized and define which components need to be synchronized and how often. Figure 2 illustrates an example Scene which consists of an environment with the default Oculus room Prefab (see Image (a)), on which a table object is placed to serve as the surface on which the exercise takes place (see Image (b)). On top of this table, the exercise objects are located. The shaped objects (see Image (c)) are physically enabled and can be grabbed, while the box with holes serves as the objective for the exercise (see Image (d)). Once activated the patient's hands are also rendered in the scene (see Image (e)).

During exercise performance, the patient controls the virtual hands, which replicate the gesture of the real hands of the patient via hand tracking [47]. The hand tracking provided by the Meta Quest device is a technology that uses cameras in the headset along with computer vision technologies to identify the hands of the user and their pose [48], [49]. In the exercise of Figure 2, when pinching the fingers or making a closed hand gesture, the physically enabled objects are picked up and can be released by opening the hand. If the objects are in the right hole, a point is given to the score tracker, otherwise, an error sound is played.

2) SESSION SETTINGS DEFINITION

In order to start a rehabilitation session, the VR Interface needs a settings package to define all the parameters for the session. These parameters can be grouped into three sets: exercise settings, general settings, and feedback settings. The *exercise settings* include the set of exercises that will be used during the session, as well as the parameters for each exercise, which depend on the type of exercise; the *general settings* define parameters that are shared through the session, such as the length in time of the session, or the skin color of the virtual hands; and the *feedback settings*, such as if the exercises will show tutorial messages, if they will signal successes and errors visually and/or auditorily.

3) SYSTEM PHASES

As illustrated in the left side of Figure 3, the system requires four phases: (i) *Preparation phase*. This can be seen as a pre-session phase where the exercises that will be done, and the parameters that will be configurable during Session Set-up, are defined; (ii) *System Set-up*. The system starts in the System Set-up stage, where the VR Interface opens a *Waiting Room* scene and waits for a connection from the Expert Interface, while the Expert Interface opens a *Connection Menu* that lists the available headsets; (iii) *Session Set-up*. Once the connection has been established, the Expert Interface shows a *Session Menu* which allows the expert to define the session parameters, and the resulting configuration package is sent to the VR Interface (see section III-B2); and (iv) *Rehabilitation Session*. In this stage the VR Interface runs the exercises and synchronizes the exercise scene state, while the Expert Interface processes the scene details and shows the *Replicated Scene*, along with a *Control Menu* where the expert can interact with the virtual world. The details for these stages are described in the sections below.

4) NETWORK MANAGER

The two applications rely on a set of shared components in the form of the Network Manager library. The main components are the Discovery Manager, the Network Manager, the Scene Replicator, and the Scene Host.

During System Set-up phase, in order to locate other headsets the *Discovery Manager* component implements the discovery protocol. The discovery can be performed in the local network, via IP Multicast, or by talking to a relay server. The details of this protocol are described in section III-C1.

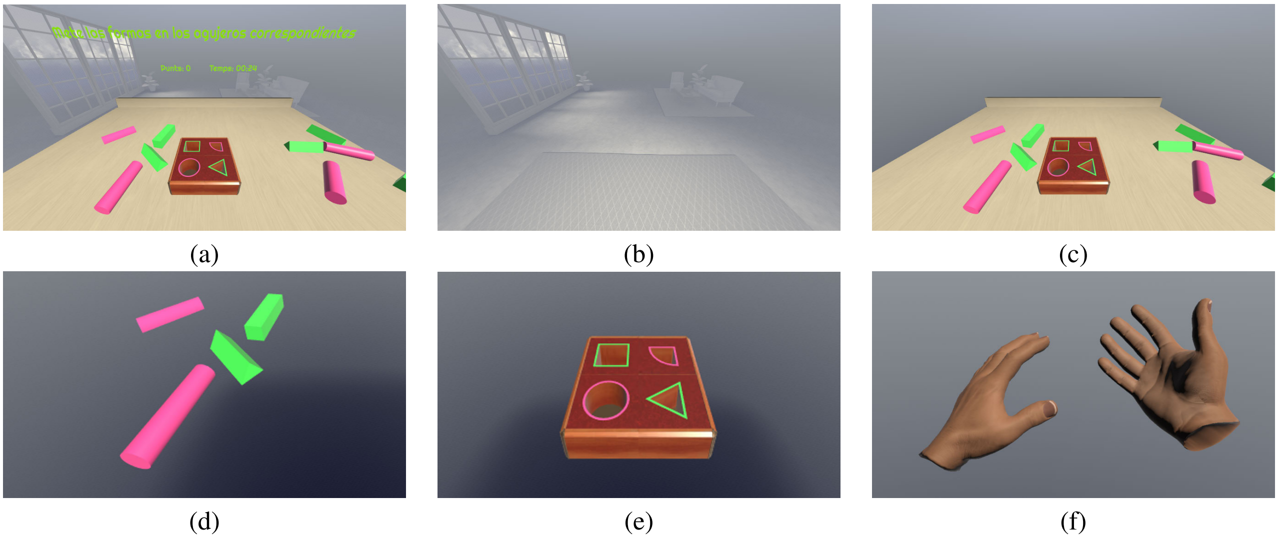

FIGURE 2. Structure of an exercise scene: (a) overall view; (b) background room; (c) exercise; (d) physically-enabled objects; (e) exercise objective; (f) virtual hands used to interact with objects through touching, pressing or grabbing.

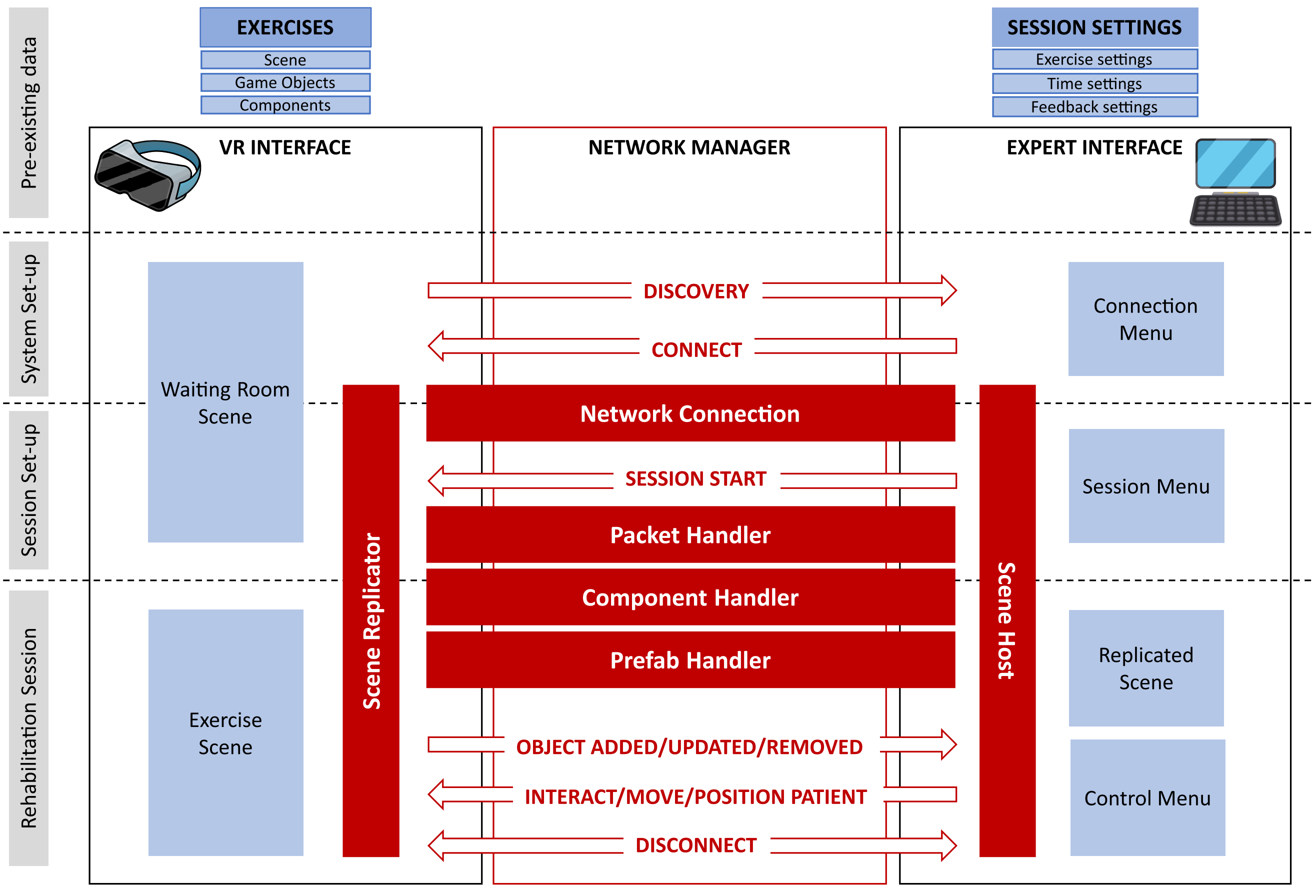

FIGURE 3. Structure of the system, where the different stages, the main modules, scenes and menus, components, and the connection details between HMD and computer device are considered.

The Network Manager component keeps track of the state of the connection between the two interfaces and it can act as both a Server and Client. The proposed system assigns the role of Server to the VR Headset, and the role of Client to the Expert Interface. This was chosen because that way connection tasks do not need to be performed on the VR Headset, and can be done exclusively via the Monitoring Device where the Expert Interface is running. The Network Manager has itself some components which it uses to perform this task. Namely: the Network Connection, the Packet Handlers, the Component Handlers, and the Prefab Handler.

During System Set-up, the Network Manager initializes itself according to which side is selected. On the Server side (VR Headset), the Network Manager initializes the network protocol in listening mode, and at the same time enables the Discovery Manager in Send mode, where the system uses IPv4 Multicast [50], [51] to send discovery packets. On the Client side (Monitoring Device), the Network Manager initializes the Discovery Manager in Receive mode, where it subscribes to an IPv4 Multicast group in order to receive the discovery packets.

When the expert chooses a headset from the list (see Section III-B6), the Network Manager creates a Network Connection to the selected headset's IP Address and port. The Network Connection uses a TCP Socket in order to transmit the packets and receive them [52]. Once this connection has been established, the system moves to the Session Set-up phase, and the Discovery Manager is disabled.

The packet protocol is implemented via a number of *Packet Handlers* which are registered in the Network Manager. Each Packet Handler manages one packet type, and has the logic to encode a packet object's data into bytes, and the logic to reconstruct the packet object from the bytes. It also defines in which connection states the packet is valid. The details of each packet are described in section III-C.

The object data is synchronized via a number of *Component Handlers* which take care of encoding and decoding the data of a component type. As an example, the Transform Component Handler synchronizes the position, rotation, and scale of an object. For Prefabricated Objects, the *Prefab Handler* is responsible for instantiating the objects in the Replicated Scene.

5) THE VR INTERFACE

The VR Interface application runs in the VR Headset and handles the rehabilitation exercises. On launch, it loads *the Scene Replicator*, a component that tracks the objects in the scene to prepare synchronization packets, and displays a Waiting Room scene, so that the person wearing the VR Headset has something to look at.

When the network connection is established, the Scene Replicator starts synchronizing the active scene. When new objects are added to the scene, the Scene Replicator sends either a *New Object* packet or a *Prefab Object* packet, depending on if the object that has been added to the scene has the Prefabricated Object component attached. If a New Object packet is used, the replicator assembles all the data from attached components whose type has a corresponding Component Handler registered. If the object is a Prefab, it sends only the prefab name and Object Identifier. When objects are removed from the scene, the replicator sends an *Objects Removed* packet with the list of object IDs that are no longer present. This is sent as a list because in cases of switching to a new scene, many objects may be removed at the same time. The replicator also tracks changes to specific values of supported components, and if any tracked value in a component has changed beyond a specified threshold, the replicator assembles an *Object Updated* packet and sends it.

When the VR Interface receives the command to start the exercise session, it decodes the settings package and prepares a queue of exercises. It then picks the first exercise from the queue and loads the appropriate scene and constructs the exercise objects as needed. Once the exercise ends, the VR Interface either loads another exercise, or returns to the Session Set-up phase and loads the Waiting Room again.

6) EXPERT INTERFACE

The Expert Interface application runs in the Monitoring Device and handles the set-up and monitoring tasks. On launch, it loads *the Scene Host component* which initializes the Network Manager, and Connection Menu.

In the System Set-up phase, the Connection Menu and displays a list of VR Headsets from the Discovery Manager. If there was a saved connection from a previous execution, the VR Interface automatically tries to reconnect to the same VR Headset device. Once a connection has been established, it waits for incoming packets and acts as follows:

- Upon receiving a New Object packet, it creates an empty Game Object, and attaches components as indicated by the packet's component list, and then reads the component values to apply them to those components.
- Upon receiving a Prefab Object packet, it looks up the corresponding prefab reference from the Prefab Manager component, which needs to be present in the scene.
- Upon receiving an Object Updated packet, it looks up the game object by the provided ID, and then if there is a part identifier in the packet, looks up the corresponding child object with that part identity. It then reads the values for the component data from the packet and applies them to the corresponding components.
- Upon receiving an Objects Removed packet, it looks up the objects with the given IDs, and removes them from the scene.

While in the Session Set-up mode, the Expert Interface shows a Session Menu which allows the expert to choose the configuration settings for the session (see section III-B2), along with a button to start the session.

While the connection is in the Rehabilitation Session phase, the Expert Interface also shows the Control Menu, which has the following panels: (i) the Camera, to allow the expert to choose between the patient's VR point of view, and one of the alternative angles configured in the VR scene; (ii) the Patient Position, to adjust it in the virtual world;

(iii) the Interact mode, to highlight the interactable objects and allow the expert to touch those and to send an Interact Object packet; (iv) the Move mode, to highlight movable objects allowing them to be moved; and (v) the System Menu, to allow disconnecting from a headset and return to the Connection Menu, and Exiting the VR app.

In the Move mode, the expert can interact with physically enabled objects by holding down the mouse/finger on an object, and dragging the finger on the screen. When the press is detected, it sends a Start Moving packet; whenever the finger is dragged enough for the position to change, a Move Object packet is sent with the relative movement; and finally when the finger is lifted from the screen a Stop Moving packet is sent.

C. PROTOCOL

The current implementation of the network protocol is based on a TCP Socket encrypted using the TLS 1.2 protocol or newer, with a packet layer on top of the data stream. Packets consist of a length value, a packet identifier, and the data. The VR Headset, as the server, provides updates about the objects in the scene and the Monitoring Device, as the client, sends action and interaction requests.

Upon receiving a connection request, the server sends a `ConnectStart` packet, with the version of the protocol. The client then responds with a `ConnectAccept` packet if it understands the given protocol version. The client then switches to a scene prepared to receive updates, and once this scene is ready, sends the `SceneReady` packet. Upon receiving this packet, starts sending `NewScene`, `NewObject`, `PrefabObject`, `ObjectUpdated` and `ObjectsRemoved` packets as necessary.

The client can send management commands to the server. Currently, the following features are implemented:

- Move Player: Allows the rehabilitator to adjust the position and orientation of the player to adapt to the needs of the patient, in case the initial head pose was not in the correct location, or they need to be closer or further away from the exercise area. This uses the `PlayerPosition` packet. The server will process the movements and respond with `ObjectUpdate` packets as appropriate.
- Perform Action: A number of actions can be set up to be recognized by the VR environment, such as Pause, Start Exercise, or Stop Exercise. These actions can optionally have a list of parameters, such as the name of the exercise to start. This uses the `PerformAction` packet.
- Interact with object: Objects can be marked as interactable. If touched or clicked while the client is in interact mode, the configured action will be run for this object on the VR end. This uses the `InteractObject` packet.
- Move object: Objects can be marked as movable. If dragged while the client is in move mode, the object will be moved on the VR end. This starts by sending a `StartMoving` packet when the mouse button is pressed down or the finger is pressed against the screen. Movements of the mouse/finger cause `MovingObject` packets to be sent with the computed world direction corresponding to the drag direction. Finally, when the mouse or finger is released, the `StopMoving` Packet is sent. The server will process the movements and respond with `ObjectUpdate` packets as appropriate.

In Figure 4 the communication protocol is illustrated. For the purposes of this explanation, the packets are organized into three categories:

- Connection management category. This has the following packets: (i)`ConnectStart`, Sent by the Server to the Client upon receiving the socket connection, to provide basic information about the connection protocol version; (ii) `ConnectAccept`, Sent by the Client to the Server to indicate that it is capable of handling the protocol version; (iii) `SceneReady`, Sent by the Client to the Server to indicate that it's ready to receive updates from the VR Headset.; and (iv) `Goodbye`, Sent by either Client or Server to indicate that it has chosen to disconnect. Allows differentiating from network loss or error.
- Scene Synchronization category. This has the following packets: (i) `NewScene`, Sent by the Server to the client when a new scene is loaded; (ii)`NewObject`, Sent by the Server to the Client when a new standalone object is added to the scene; (iii) `PrefabObject`, Sent by the Server to the Client when a prefab object is added to the scene; (iv) `ObjectUpdated`, Sent by the Server to the Client when an object's component values change; (v) `ObjectsRemoved`, Sent by the Server to the Client when objects are removed from the scene.
- Remote Management category. This has the following packets: (i) `PlayerPosition`, Sent by the Client to the Server to move or rotate the coordinate origin used to position the player in the virtual environment; (ii) `PerformAction`, Sent by the Client to the Server when a remote action (such as pausing, or stopping the current activity) is requested; (iii) `InteractObject`, Sent by the Client to the Server when the Expert has interacted with an object; (iv) `StartMoving`, Sent by the Client to the Server when the Expert has started moving an object, and it should temporarily stop applying physics and other movement logic to this object; (v) `MoveObject`, Sent by the Client to the Server when the Expert is moving an object. Multiple of these packets can happen between `StartMoving` and `StopMoving`. This packet is only valid if it happens between `StartMoving` and `StopMoving`; and (vi) `StopMoving`, Sent by the Client to the Server when the Expert has stopped moving an object and its physics and logic can be enabled again.

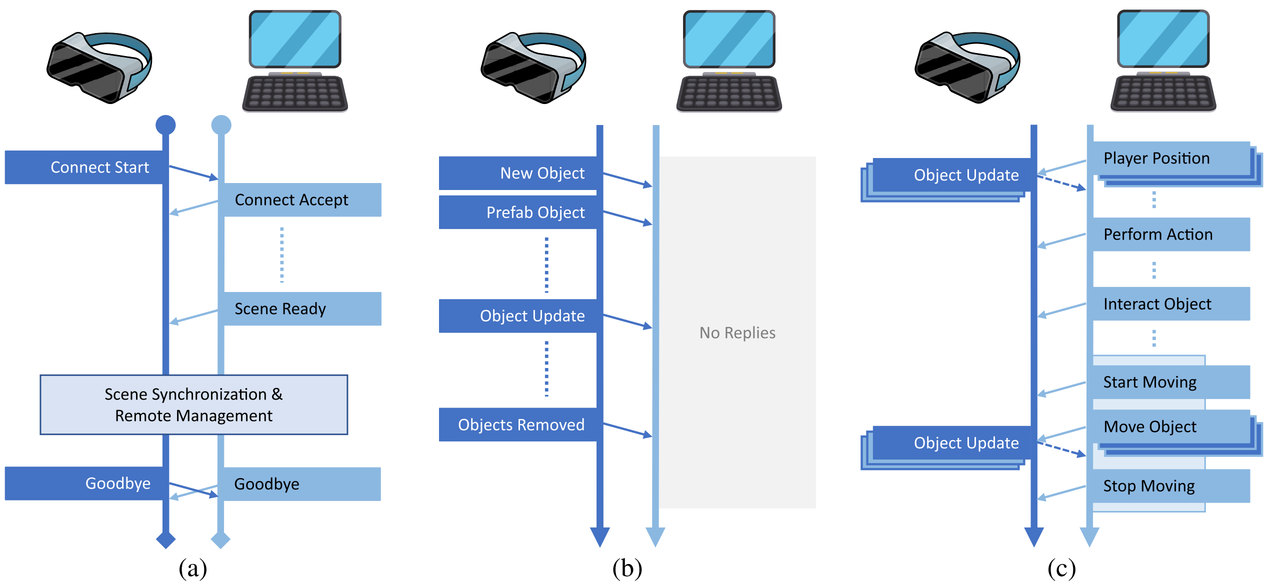

FIGURE 4. Communication protocol: (a) connection management; (b) scene synchronization; (c) remote management.

1) DISCOVERY PROTOCOL

The discovery protocol is used by the VR Interface to announce its presence to the Expert Interface.

For Local Network discovery, the system uses Multicast feature of the IP protocol [51]. The process is as follows: a Multicast IP Address is configured to be the same on both devices; if it is not connected to an Expert Interface the VR Headset periodically sends an announce packet to the Multicast IP, and while searching for devices, the Expert Interface joins the Multicast group and waits for packets to be received. If the packet has valid content, it is added to the list and displayed in the Expert Interface. Entries that have not been seen for a while get removed.

For telerehabilitation, the process is similar but instead of using Multicast, VR Interface announces its presence to the relay server, and the Expert Interface connects to the relay server to receive the most updated list.

D. EXERCISE ADAPTATION PROCESS

To enable remote monitoring to work with existing exercises requires making certain changes to the software. These changes correspond to the objects that will be used by the exercise, and the configuration parameters that will be provided by the expert interface.

Particularly, the changes that need to be done in the VR interface are:

- A new component that defines the synchronization properties is added to every object that need to be synchronized (that is, all objects that are not decorations already built into the virtual environment on which the exercise is constructed). In this component, the list of properties that will be synchronized can be defined, along with the minimum change needed to mark as modified, and the minimum time interval between synchronizations of each property.
- Objects that are made of different parts bundled into one (a prefab in the terminology used by the Unity engine) are given a prefab name that will be used to identify the same object on the expert monitoring module.
- Objects that the expert should be able to interact with or move while providing aid to the patient, can have the *remote interactable* or *remove movable* options enabled to allow the interface to apply those functions to these objects.
- A handler for receiving the configuration from the expert interface is added to the exercise controller with a set of configuration values that the expert interface will provide.

Similarly, the changes that need to be done in the expert interface are:

- A new configuration panel is defined for the new exercise, and a screenshot thumbnail is assigned to it. A set of configuration values are defined with type of configuration (text, yes/no checkbox, range slider, select among a list of options).
- The objects that will appear during exercise are defined, and assigned the same names as in the VR interface.

E. TECHNICAL SPECIFICATIONS

Regarding technical specifications of the system, the expert module requires only a basic laptop for office use, when using modern hardware, or a medium-high spec laptop for older hardware, running Windows 10 operating system or newer. It can also run on a medium-high spec Android mobile phone or tablet. Other operating systems (Linux, macOS, iPad OS) would be possible but have not been tested. The

VR rehabilitation module has been designed for the Meta Quest 2 standalone mobile headset. While tethered PC VR headsets are technically compatible, they have been avoided due to the cables restricting movement, which can be a burden in a rehabilitation environment. Other VR headsets may be compatible if they are supported by the Unity game engine used to develop the VR experience. However, compatibility with these alternative headsets has not yet been tested.

IV. RESULTS

In this section, the testing scenarios, with patients and with developers, and the evaluations that have been carried out to measure the advantages of the proposed system are presented.

A. TESTING SCENARIOS WITH PATIENTS

The testing scenarios for the evaluation of the system have been designed after several sessions as spectators in a rehabilitation center. Particularly, acute stroke patients with moderate to severe upper limb impairment were considered. For these, the rehabilitators using their own software prepared a session with three exercises which required approximately ten minutes each to be solved.

The rehabilitation sessions started at a set time, when the patients arrived at the rehabilitation room. The rehabilitator prepared a Meta Quest 2 [29] device by turning it on and running the software. Then, an explanation was given to the patient indicating the goal of each exercise. In addition, exercises provide textual descriptions of the goals. After the explanation, the session was prepared within the headset, and the patients were equipped with it. Rehabilitators then monitored the patient via a tablet device running the Meta Quest software [53], which allows casting a video feed from the VR Headset into the mobile device.

During rehabilitation, three situations that truncated the session were detected. The first one is when the patient does not understand how the exercise works and needs more explanation. In this case, the rehabilitator has to describe the exercise again, giving more details to provide guidance. The second one is when the patient encounters difficulty during exercise execution because an exercise object has become located out of reach of the patient and needs to be moved. In this case, the rehabilitator needs to take the headset from the patient and put it on themselves, then adjust the position of the object by directly interacting with the virtual world. The third one is when the patient's hands are not visible to the headset's hand-tracking software and the rehabilitator has to help the patient position their hands such that the hand-tracking software can find them again. Furthermore, due to limited network performance, the monitoring software sometimes did not work properly, showing a poor image or disconnecting. In these cases, the rehabilitators had to perform the rehabilitation without monitoring, relying solely on patient feedback. This led to increased pauses due to the complexity of providing explanations to the patient and having to remove the headset from the patient more times and for increased periods. These situations led to patients' frustration, reducing the motivation and attention of both the patients and the rehabilitator.

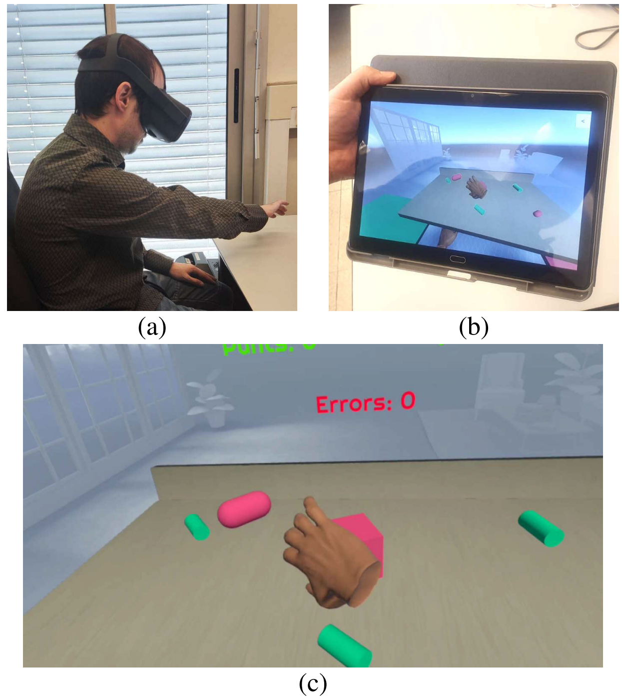

FIGURE 5. **Testing scenario: (a) patient with headset; (b) Expert Interface in the tablet device; (c) VR Interface in the headset.**

After this observational phase, to evaluate the system a rehabilitation session has been simulated in three scenarios. These are: (i) a standalone scenario (**S1**) where the patient is equipped with the Meta Quest 2 headset, but no monitoring software is used by the rehabilitator; (ii) a video feed scenario (**S2**) where the patient is also equipped with the same headset, and the rehabilitator uses a tablet device with the Meta Quest monitoring software, which only provides a video feed of the exercise as seen by the patient; and (iii) a remote monitoring scenario (**S3**) where the patient is also equipped with the same headset, and the rehabilitator uses a computer running the Expert Interface proposed in this paper, which can replicate the virtual world and allows interaction (see Figure 5).

For the tests, the rehabilitation sessions have been divided into five phases. These are: (a) *Launch App*, when the software gets launched in the headset and, if applicable, in the computer; (b) *Prepare Session*, when the expert chooses a session with three exercises, set to last for 10 minutes, with the default settings for each exercise; (c) *Patient needs an explanation*, when the patient does not understand how the exercise works, and the rehabilitator needs to interact with the virtual world in order to provide guidance; (d) *Patient encounters a difficulty*, when an exercise object has become located out of reach of the patient and needs to be moved; (e) *Finish Session*, when the software on both the headset and computer is closed. It has been considered a session where the patient has at least one interruption that requires guidance, and at least one interruption because an object has become out of reach.

B. TESTING SCENARIO WITH DEVELOPERS

In addition to patients and doctors, technologists have emerged as a fundamental part of rehabilitation environments, focusing on the design and development of new technology-based solutions that improve the efficiency and effectiveness of rehabilitation processes. Therefore, it is essential to consider the developers' experience with the system. It is important to analyze the workload implications for rehabilitation exercise programmers using the proposed system, compared to the standard method where interaction with the virtual reality environment by the rehabilitator is not possible. Evaluating how the system affects the workload and experience of developers in these scenarios is crucial.

Four developers will use the proposed system for the duration of a week, where they will have the opportunity to adapt rehabilitation exercises to the remote monitoring system. Upon completion of the exercise creation process, they will be interviewed to gather the time spent using the system and their opinions regarding usability, functionality, ease of use, and interest in using the system in the future. They will be provided with a questionnaire consisting of a first section with two preliminary questions for the number of exercises they adapted, and the time spent performing those adaptations, a second section with four questions to answer using a Likert scale from 1 to 5, indicating from least to most interest, and a final open question to gather any comments they wish to make. For the Likert scale questions, the relationship between the item to be considered and the formulated question, presented as item-question is the following one: usability-*The System is useful for adapting exercises to remote monitoring*; functionality-*The System offers the necessary features to adapt exercises for remote monitoring*; ease of use-*The System is easy to use*; and interest in using the system in the future-*I would use the system again in future projects to implement remote monitoring*.

C. EVALUATED METRICS

To evaluate the system from the patients/rehabilitator point of view two metrics have been considered: *time overhead*, the time spent not performing rehabilitation tasks; and *system performance*, the speed and resource usage of the system. To evaluate the system, from the developer's point of view as a metric the *development effort*, i.e., the complexity of preparing the system for new exercises and objects, has been considered. In addition, developers' opinions concerning *usability*, *functionality*, *ease of use*, and *interest in using the system in the future* have been taken into account.

- Time overhead (T_o) has been defined as the time when the patient is not actively engaged in rehabilitation (see equation 1). This includes the time where the rehabilitator has to use the HDM (T_r), the time where the HDM is removed and not actively used (T_w), and the time where the HDM is being transferred from one person to another (T_t). To measure these times it is considered the rehabilitation session started with the headset and computer turned on, but without the application running.

$$T_o = T_r + T_w + T_t \tag{1}$$

- System performance has been measured considering, three parameters: (i) Frames per second (fps), representing the rate at which the headset device can update the display, and computed by measuring a period and averaging the numbers of frames presented during that period ($\frac{N_{frames}}{T_{end}-T_{start}}$). Because the precise timing is not provided by the VR-HMD device, these time periods have been measured using the update intervals provided by the Unity game engine. A conservative benchmark of 75 fps has been considered [54], where higher numbers are better; (ii) Network bandwidth usage, measured as the number of bytes of information presented during a period of time and obtained using a network monitoring software that provides network transfer totals. A benchmark of no more than 5*Mbps* has been considered adequate based on the statistics provided by the Speedtest Global Index as of June 2024 [55]. Lower numbers are better as they allow the system to continue working in situations of more limited connection quality; and (iii) Effectiveness of the monitoring in terms of how easy it is for the rehabilitation expert to understand what the patient is doing, obtain useful information from the provided display, and be able to judge the progress of the rehabilitation.
- Exercise *development effort* has been measured in terms of the steps needed to adapt an exercise implementation to each monitoring method and the time it takes to perform those steps. As a point of reference, it has been observed through our experience developing a rehabilitaton exercise that the development requires around 40 to 50 hours.
- *Usability*, *functionality*, *ease of use*, and *interest in using the system in the future* have been measured from the developers' answers to the questionnaires.

D. TIME OVERHEAD

Time overhead has been computed for each phase of a rehabilitation session and for each one of the considered scenarios. The obtained results for the case of one guidance interruption and one out of reach interruption are illustrated in Figure 6 where the times with headset on expert, without headset, with headset on the patient and putting on or removing headset have been represented. From the plotted results per phase, and from left to right, it can be observed that for the Launch app phase, scenario S2 is the one that takes most time, specially time where the headset is not in use. This has been observed to be caused by the time

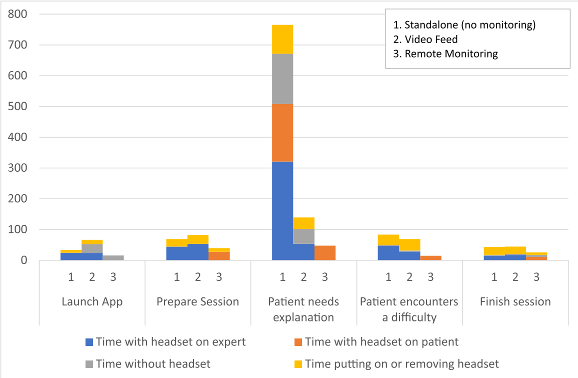

FIGURE 6. **Time overhead computed for each phase of a rehabilitation session and for each one of the considered scenarios.**

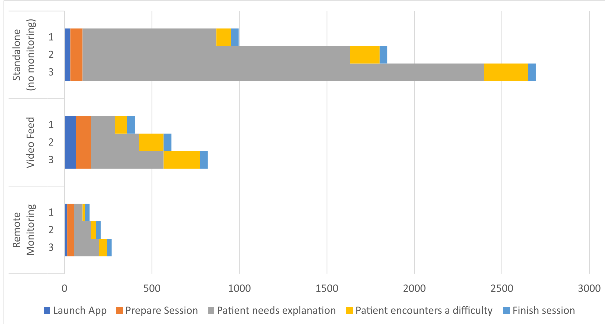

FIGURE 7. **Session Overhead Totals for each tested scenario, considering the different phases of a rehabilitation session, in the cases for one, two and three interruptions of each type.**

spent navigating the Video monitoring app and enabling the Cast feature within the app, which requires multiple touch interactions. Focusing on the time when the rehabilitator has the headset on themselves, both scenarios S1 and S2 have approximately the same time overhead since both require interacting with the headset in order to launch the software. On the contrary, the proposed system greatly reduces the total overhead time, as seen in scenario S3, which reduces the time the patient is waiting for the rehabilitation to start. With regards to the Session preparation phase, it can be seen that scenarios S1 and S2 have similar overhead, where the expert has had to remove the headset from the patient and put it on themselves, leading to more overhead. In scenario S3, the proposed system allows the HDM to remain on the patient. Regarding Patient needs explanation, it can be seen that a system with no monitoring (scenario S1) leads to the biggest overhead, due to the inability of the expert to see the virtual world without putting on the headset. With the video feed of scenario S2 the difficulty is greatly reduced, but the expert still needs to remove the headset from the patient in order to demonstrate the explanation. With the proposed system, the expert can interact with the virtual world from the Expert Interface, which allows the patient to keep the headset on. Focusing on the Patient difficulties phase, it can be seen that scenarios S1 and S2 have similar overheads, since both require that the expert puts on the headset. The proposed system allows interacting with the exercise objects directly from the Expert Interface. Finally, with regards to Finish session phase, it can be seen that scenarios S1 and S2 require the expert to put on the headset in order to exit the software, while the proposed system allows existing the software remotely.

Figure 7 illustrated the total overhead for each tested scenario, considering the different phases of a rehabilitation session, in the cases for one, two and three interruptions of each type. For scenario S1, the total overhead was 996 seconds, growing to 2694 seconds for the case of multiple interruptions. For scenario S2, the numbers are lower, 403 seconds growing to 819 for three interruptions. The proposed system, in scenario S3, shows only 144 seconds for one interruption, a reduction of 64% concerning scenario S2 and 85% with scenario S1 thanks to the improved ability for the rehabilitator to see and interact with the virtual environment without removing the VR-HMD from the patient's head. These differences grow to 66% and 90% respectively, in the case of 3 interruptions of each type.

It can be seen that the proposed system shows a much lower time overhead, and this difference becomes more meaningful the more interruptions there are. In fact, for scenario S1 the interruptions were so cumbersome that even in the case of one interruption of each type the time overhead was longer than the intended session length, while the proposed system shows in scenario S3 that even for multiple interruptions the time overhead remained short.

E. SYSTEM PERFORMANCE

To evaluate system performance, scenario S1 establishes our baseline, since it has full frame rate and no network usage. It has been observed that scenario S2 lowers the fps by 14%, with a network usage of over 8mbits per second (bps); the proposed system has much lower impact on both areas, allowing the performance reduction to be only 2% and remaining above the 75 fps target, with a network usage of just above 900k bps, noting that these numbers may change based on the complexity of the exercise being monitored. In the case of low Wi-Fi signal reception, the video feed of scenario S2 becomes extremely blurry and with a lot of artifacts and interruptions, while the proposed system manages to maintain a connection.

F. DEVELOPMENT EFFORT

The first section of the questionnaire provides us with insights into the amount of time an experienced developer using the system for the first time needs to spend in adapting exercises. As described in section III-D, this adaptation requires that developers make changes to the VR interface including adding synchronization properties to objects, naming prefabs for expert identification, enabling remote interactions, and adding a configuration handler. This time has a wide range from 45 minutes to 3 hours per exercise, which is between 1% and 6% of the exercise development time, but the effort depends majorly in the kind of objects used by the exercises and the information that these objects need to synchronize. It has also been provided as an observation that, as expected, the development effort was greatest on the first exercises and reduced with practice.

It should be noted that this development effort happens during the development phase and does not affect the real-world application of the exercises or their effectiveness.

G. DEVELOPER IMPRESSIONS

The results of the four questions in the second section of the questionnaire have been as follows: for the *usability* question, all four answers have been 5/5; for the *functionality* question, the answers average 4.75/5; for the *ease of use* question, the answers average 3.25/5; and for the *interest in using the system in the future* question, the answers average 4.0/5. The additional comments clarify that these ratings are due to somewhat steep learning curve caused by the differences in development requirements compared to traditional development, and in part due to insufficient documentation.

H. LIMITATIONS

Although the results from the tests indicate that the proposed system is effective, some limitations of the carried out study should be stated.

First, focusing solely on same-room rehabilitation scenarios with a 1:1 therapist-patient ratio might limit the generalizability of the findings to real-world situations where telerehabilitation or multiple patients are involved. To address this limitation, future studies should be designed to evaluate the system's effectiveness in telerehabilitation settings and with multiple patients.

Second, the use of an older Oculus Quest 1 headset with lower performance could potentially affect the user experience and potentially the effectiveness of the rehabilitation exercises. Future studies should ideally use the targeted hardware (Meta Quest 2) or account for potential performance differences.

Third, testing with only one headset model limits the generalizability of the findings to other VR devices with potentially different functionalities, like hand tracking algorithms. Future studies should consider testing the system with a broader range of VR headsets to assess its compatibility and effectiveness across different platforms.

Fourth, while the developer experience was positive, it was noted by more than one of the developers that the system as it exists right now can be hard to learn and that better tools for integrating the system into the development process, and better documentation for the different features of the system, would be of great aid.

Additionally, the proposed solution has been designed to make use of assets already present on both the VR and expert machines, and currently does not support the synchronization and interaction with expert-created models and textures, limiting the possibilities for personalized content. Additional features will have to be implemented to support these options.

Finally, it should be noted that the proposed system has not been compared with state-of-the-art techniques because the available papers focus solely on usability and user experience, lacking technical information about algorithm performance [56], [57], [58], [59].

As an addendum, it's worth noting that the use of the Unity engine means that the primary focus is on exercise environments developed with Unity. However, the protocol is versatile and can be implemented in other environments. It should integrate easily into existing clinical workflows in real-world rehabilitation settings, assuming these settings have an internet connection.

I. DISCUSSION

In the context of rehabilitation, remote assistance involves delivering therapeutic support, guidance, and monitoring from a distance. This allows healthcare professionals to continuously care for and supervise patients without requiring them to be physically present. Utilizing telecommunication technologies and digital tools, remote assistance ensures that rehabilitation specialists can offer immediate support, personalized guidance, and effective monitoring, all of which are crucial for optimizing patient outcomes.

However, in virtual reality scenarios where patients wear HMDs, remote control introduces complexity. Specialists must oversee and manipulate elements within the virtual environment, requiring advanced technological solutions to ensure continuous interaction and therapeutic efficacy, whether sessions take place in the same room or remotely.

Addressing these challenges highlights the limitations of generic solutions, which provide only visual monitoring without interactive functionalities. Multiplayer approaches are also impractical for rehabilitation scenarios because therapists must manage sessions in the physical environment. In contrast, our solution leverages VR advantages to enable therapists to effectively oversee real-world scenarios and seamlessly interact with the virtual environments while concurrently providing in-person rehabilitation assistance and monitoring to both VR and traditional rehabilitation patients. This integration creates a novel and robust platform where therapeutic strategies can dynamically evolve.

This first prototype has been primarily focused on providing effectiveness for the patient and rehabilitator, and the survey results show that the developers' ease of use is not yet ideal. Despite that, the developer experience has been highly rated in terms of usability and functionality, and all the developers have stated they would continue using this software in future projects with the expectation that the system will be further refined and more documentation will be provided.

V. CONCLUSION AND FUTURE WORK

To ensure the effectiveness of HMD-VR-based rehabilitation, it is crucial to address both patient needs and those of the rehabilitator. In this context, providing rehabilitators with the ability to control and interact with virtual scenarios during patient sessions is highly valuable. To this end, a new system has been proposed to enhance the control and monitoring of rehabilitation sessions.

Unlike traditional systems that require removing the VR headset to address issues, the proposed system allows rehabilitators to intervene seamlessly within the virtual environment. This reduces interruptions and enables better management of patients, whether by handling more patients or dedicating more time to each one. The system's replicated view facilitates easier monitoring, while its interactive features help rehabilitators assist patients with tasks like locating objects or understanding exercise goals. Technically, the system provides a low-bandwidth, low-resource solution for synchronizing exercise visuals and interacting with the virtual environment. It also allows for adjustable visual quality in the expert interface, supporting a wider range of devices compared to direct scene transfers. These advancements enhance the overall efficiency and effectiveness of VR rehabilitation.

Future work will focus on evaluating the system across a broader range of rehabilitation scenarios, including support for multiple patients simultaneously. We will also expand compatibility to include other HMD brands and alternative devices such as mobile phones, tablets, and computers. Additionally, the system will be enhanced to support dynamic content packs and patient-specific materials, and we will refine the functionality for developers to streamline the integration of remote monitoring into their exercises. Moreover, the system will be updated to address more pathologies and rehabilitation movements, beyond its current focus on upper extremity rehabilitation for post-stroke patients.

DECLARATIONS

a: CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

b: OPEN ACCESS

DATA AVAILABILITY

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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