# Mixed reality (MR) Enabled Proprio and Teleoperation of a Humanoid Robot for Paraplegic Patients

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***Abstract*—Paraplegia is a disability caused by impairment in motor or sensory functions of the lower limbs. Most paraplegic subjects use mechanical or motorised wheelchairs for their movement, however, this may limit the capability of patients to independently perform common activities of daily living (ADL). In this paper, a novel mixed reality (MR) enabled proprio and teleoperation framework for a humanoid robot is presented. The framework can be operated by a paraplegic person by using inputs from an MR headset. The framework enables varied and unscripted manipulation tasks in a realistic environment, combining navigation, perception, manipulation, and grasping. The impaired operator can make use of a wide range of interaction methods and tools, from direct teleoperation of the robot's full-body kinematics to performing grasping tasks or controlling the robot's mobile base. The adopted humanoid robot is the EVEr3 Humanoid Research Robot from Halodi Robotics, while the Oculus Rift S is chosen as MR headset. To demonstrate the potential of the proposed framework, a human subject study is presented. In this study, a home/workplace environment is rendered with MR by combining physical shelves and everyday objects, such as goods to be grasped, with simulated elements, such as the robot avatar and the control interface. A paraplegic subject is involved in the study. Results suggest that the proposed MR-enabled system improves the patient engagement and illusion of presence.**

***Keywords*— augmented reality, humanoid robot, paraplegia**

## I. INTRODUCTION

The capacity to move around, experience our surroundings, and transfer to other locations to participate in everyday activities is a necessary feature in human life. People with mobility impairments may be unable to do so because of their condition. Many disabled persons can become more mobile with the use of prostheses or wheelchairs. However, paraplegic individuals with limited lower limb functionality may find it difficult to conduct activities of daily living (ADLs). In fact, paraplegia is a paralysis starting in the thoracic (T1-T12), lumbar (L1-L5) or sacral (S1-S5) area [1], [2], which results in the inability to voluntarily move the lower parts of the body. However, persons with paraplegia usually possess good functioning of the arms and hands. Consequently, for paraplegic patients, teleoperated robotics could provide a formidable improvement in the quality of life [3]. A teleoperated robotics system is commonly formed by two different scenarios: the operator site where the master and the human operator are located, and the remote site where the robot, performs the remote task. It clearly shows that the human is "isolated" from the working environment and is to be safe at every moment. However, a relatively new concept of robotics teleoperation, called "proprio and teleoperation", introduces a scenario where sometimes both areas, the operator and remote environment are the same, but not at all times [4]. The human operator teleoperates the robot whose working environment includes himself or herself. This paradigm enables the possibility of adopting teleoperated robotics in a home environment or a work environment.

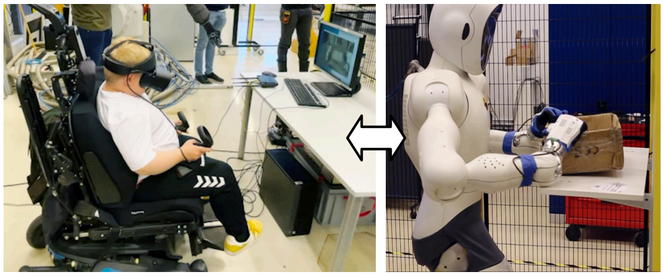

Fig. 1: Proposed idea: a mixed reality (MR) enabled proprio and teleoperation of a humanoid robot for paraplegic patients.

In line with these same control paradigm, this paper introduces a novel mixed reality (MR) enabled proprio and teleoperation framework for a humanoid robot, as shown in Figure 1. The objective is to develop a teleoperated robotic system that will assist paraplegic people with ADLs such as eating, drinking, shaving, grooming, or just fetching goods from shelves or the floor. To achieve this, the adopted humanoid robot is the EVEr3 Humanoid Research Robot from Halodi Robotics [5], while the Unity gaming engine [6] and the Oculus Rift S [7] controller are employed for augmenting the patient capabilities. A human subject study is conducted to show the possibilities of the proposed framework. In particular, MR is used to create a home/workplace setting by integrating physical shelves and everyday objects, such as graspable goods, with simulated components, such as the robot avatar and control interface. The study includes a paraplegic participant. The proposed MR-enabled framework appears to increase patient engagement and the illusion of presence, according to the findings.

The paper is organised as it follows. A review of the related research work is given in Section II. In Section III, the proposed framework architecture is presented. The considered human subject study is described in Section IV. In Section V, experimental results are outlined. Finally, conclusions and future works are discussed in Section VI.

## II. RELATED RESEARCH WORKS

Independence, a sense of control, and freedom are some of the major elements that are intimately correlated with life satisfaction and health (both psychological and physical) for older individuals and persons with motor impairments [8]. Confidence in one's capacity to perform diverse activities is central to one's psychological functioning [9]. A better sense of control over one's life is positively linked with improved healthand a lower mortality rate. To enable or augment the capacity of people with mobility impairment to perform diverse ADL, a number of assistive robot systems [10], such as desktop workstations with robotic arms [11], wheelchair-mounted robotic arms [12], powered orthotic and prosthetic arms [13], mobile manipulators [14], and wearables [15] have been developed in the past.

Although these robotic assistive robot systems have shown a great potential, human-robot interaction (HRI) has lagged behind the mechanical capabilities of the robotic systems themselves. This is particularly true for paralysed users, whose control is restricted to low-bandwidth joystick, sip-and-puff, or brain–machine interface (BMI) outputs operating individual joints or robotic degrees of freedom (DOF) [16]. Recent advances in autonomous robotics, such as computer vision sensing and intelligent trajectory-planning algorithms, hold extreme promise for enhancing assistive robot systems from a HRI perspective. Augmented reality (AR) expands on these advances by overlaying computer-generated visual input on the natural world with which the user is engaging, allowing for a more seamless integration into the user's daily life. For example, an AR control interface that accepts multiple levels of user inputs to a robotic limb using noninvasive eye tracking technology to enhance user control is presented in [16]. With the aim of reducing even further the visual-split that different input and output modalities of robot control, mixed reality (MR) could potentially facilitate communication between humans and robotic systems. In this perspective, the opportunities and challenges of using MR in human-robot collaboration are discussed in [17]. The focus is to bring input and output modalities closer together.

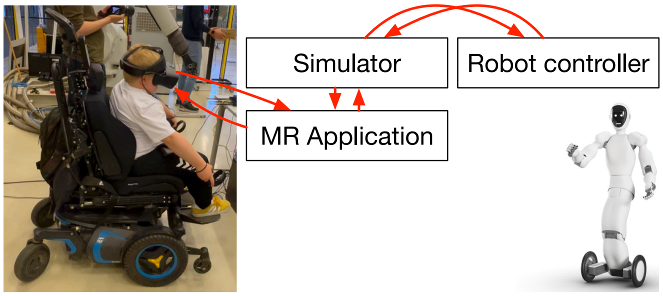

Fig. 2: The high-level representation of the framework.

Although the fundamental concepts are provided by these seminal works, a MR enabled proprio and teleoperation of a humanoid robot for paraplegic patients is still missing to the best of our knowledge. The main goal of this paper is to contribute towards the development of such a framework.

## III. FRAMEWORK ARCHITECTURE

In this section, we describe the proposed framework architecture. The high-level representation of the proposed framework is shown in Figure 2. The underlying idea is that the robot operator can provide the desired control inputs from an MR application. The interaction is enabled by a simulator where the robot avatar and the control interface are integrated. The desired control inputs are forwarded to the robot controller to be actuated by the robot.

In details, as depicted in Figure 3, the following components are considered for the proposed framework architecture:

- EVEr3 Humanoid Research Robot. The EVEr3 Humanoid Research Robot from Halodi Robotics [5] is a fully integrated platform. The robot is provided with a wheelbase design. The wheelbase consists of two differentially steered wheels and a support point on the back. The robot platform enables robotics researchers to concentrate on developing new algorithms and solutions rather than needing to first create a platform. The robot's close-to-direct drive transmission technology enables for simple direct force control interactions with the actual environment. The robot is built from the ground up to have the smallest simulation gap feasible, making machine learning development, testing, and deployment as simple as possible. The EVEr3 Humanoid Research Robot has two on-board computers, a real-time PC running critical tasks and a high performance personal computer (PC) for perception tasks.

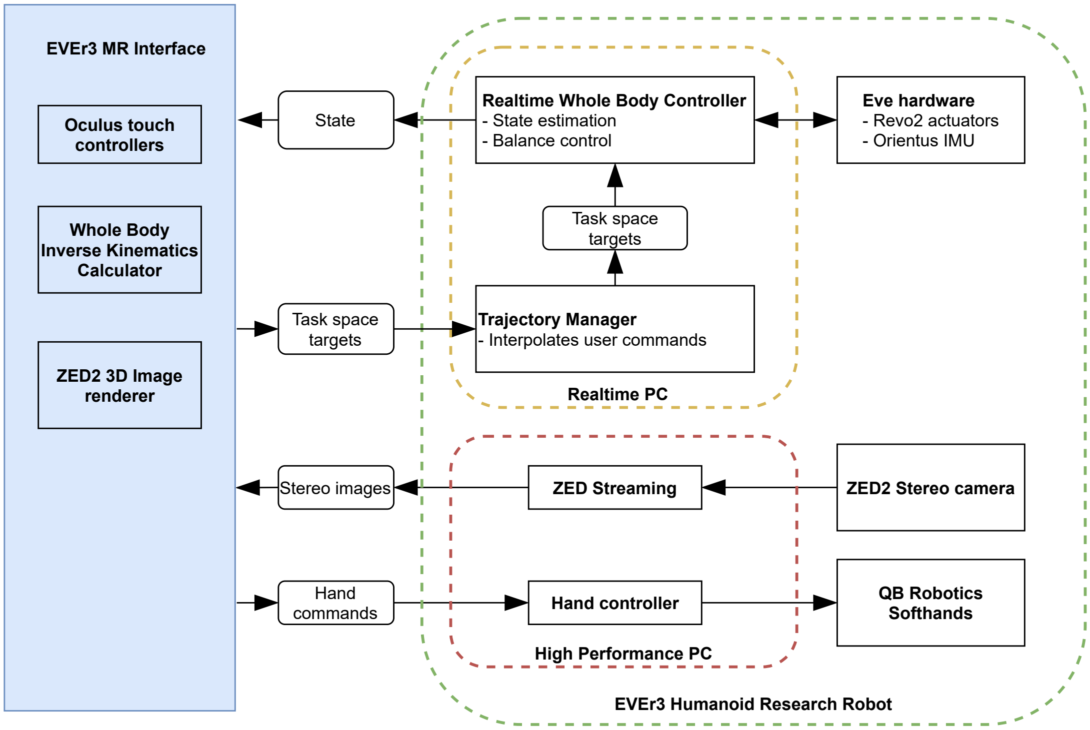

Fig. 3: The proposed framework architecture.

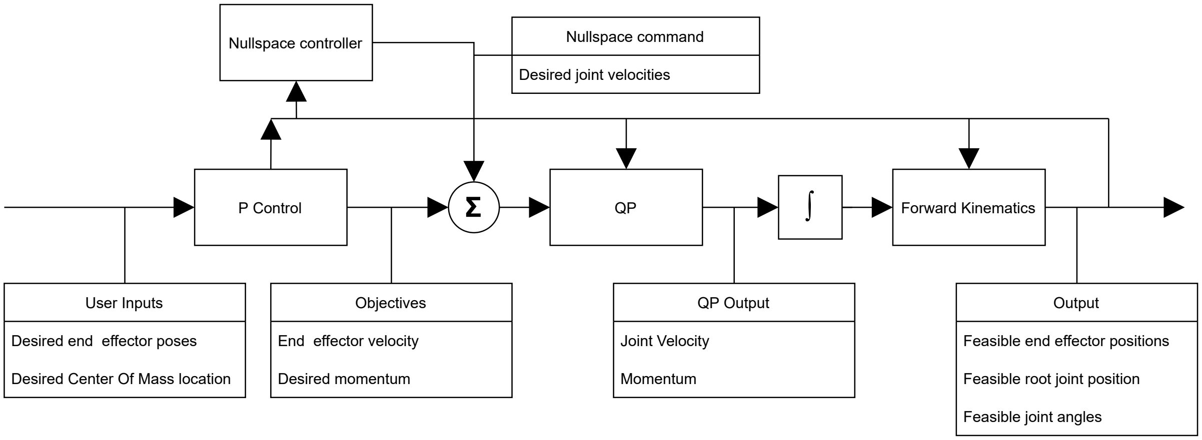

Fig. 4: Inverse kinematic calculator block diagram.

- EVEr3 MR application. The EVEr3 MR application provides the user an intuitive control interface. The interface is based on a virtual robot model, updated with sensor data. The user is virtually positioned with respect to the wheelbase and is free to move around. The stereo image captured with a ZED2 [18] stereo camera is projected on a virtual 3D view screen, which is attached to the virtual robot model. The decoupling between the view screen and the users head motion avoids motion sickness inside the MR environment. The MR application is developed in Unity [6]. Inside the MR interface, the user can move virtual targets for the hands by using the Oculus touch controllers. The desired head orientation is mapped directly to the orientation of the headset.
- Whole-body inverse kinematics. A whole-body inverse kinematics controller (WB-IKC) is used to calculate the optimal feasible whole-body pose for the robot, given a set of inputs, i.e., desired hands and head locations. The block diagram is shown Figure 4. The inverse kinematics

problem is formulated as an iterative Quadratic Program (QP), which optimises for the set of joint velocities $\mathbf{v}_d$ that are the closest to the given inputs after the next integration step. The QP is formulated as:

$$\underset{\mathbf{v}_d}{\text{minimise}}\ \frac{1}{2}(J\mathbf{v}_d - p)^T C_w (J\mathbf{v}_d - p) + \frac{1}{2}(A\mathbf{v}_d)^T C_h (A\mathbf{v}_d) + \frac{1}{2} \cdot c_v \mathbf{v}_d^T \mathbf{v}_d, (1) \qquad (1)$$

where,

$(J\mathbf{v}_d - p)^T C_w (J\mathbf{v}_d - p)$ are the motion tasks. The desired motion tasks $p_i$, where $i = 1...n$ is the identifier for the task, like desired hand velocity, centre of mass velocity and desired joint velocities, provide objectives to the optimisation problem in the form of $J_i\mathbf{v}_d = p_i$, where $\mathbf{v}$ are the desired joint velocities and $J_i$ is the Jacobian matrix. $J$ is the combination of the task jacobians $J_i$. The motion tasks are added as an objective with the weight matrix $C_w$, allowing prioritisation of tasks. This allows the WBC-IK to track hand velocities by moving the pelvis. To enforce a feasible solution for balance, the center of mass velocity has the highest priority, followed by the hand velocities. A low weight is given for the pelvis velocity, placing the pelvis in an upright position if possible.

$(A\mathbf{v_d})^T C_h (A\mathbf{v_d})$ minimises centroidal momentum. $A$ is the centroidal momentum matrix used to calculate momentum $h = A(\mathbf{q}_d)\mathbf{v_d}$. Minimising centroidal momentum results in less motion of the heavier links, like the torso, in favour of moving the light links like the arm.

$\frac{1}{2} \cdot c_v \mathbf{v}_d^T \mathbf{v}_d$ ensures that the resulting hessian matrix is invertible. Also, it has been found that increasing $c_v$ can result in a less aggressive behaviour of the robot.

A proportional (P) controller is used to convert desired positions into desired velocities for the motion tasks. To handle redundancy, such as extra DOF in the arm, and singular configurations, a set of preferred joint velocities is projected into the nullspace of the set of desired motion tasks $p_i$, These preferred joint velocities are obtained from P-controllers that aim at bringing the joints closer to a preferred robot pose.

After the QP, the joint velocities are integrated to calculate joint angles and a forward kinematics calculation is performed to provide task space positions. The task space positions are commanded to the robot, and the results are used for the next iteration of the WB-IKC.

- Real-time Whole-Body Controller. The whole-body controller provides an efficient push recovery and balancing controller that allows the user to be confident in moving the robot without worrying about falling over, as described in [19].
- Trajectory Manager. The trajectory manager receives desired task space commands from the EVEr3 MR Interface and filters those with a first order low-pass filter, before sending them on to the Real-time Whole-Body Controller. The filtering smooths out possible jitters introduced in the network layer, as well as the update rate of the MR application.
- ZED Streaming. Visual sensing is provided using a ZED2 stereo camera mounted in the robot head. The head has a single degree of freedom, allowing the robot to look up and down. The video stream is compressed by using High Efficiency Video Coding, also known as H.265 and streamed using the Real-time Transport Protocol (RTP) to the EVEr3 MR Interface.
- Hand Controller. The robot has two QB Robotics SoftHands [20], controlled trough a ROS2 [21] node. The SoftHands have a single actuator and mechanically adapt to grasp a wide variety of objects.

## IV. HUMAN SUBJECT STUDY

A home/workplace scenario is created by integrating physical shelves and everyday objects, such as graspable goods. MR is employed to render components, such as the robot avatar and control interface.

A paraplegic person is included in the study as the human subject. The human subject is affected by a rare congenital muscle disease known as Duchenne Muscular Dystrophy [22]. This condition weakens all the muscle groups in the body, resulting in the subject having limited strength. The subject is therefore dependent on using a wheelchair in everyday life. During the study, the human subject performs simple grasping, release, and human-robot handover tasks.

A qualitative interview was performed immediately following the test session. This was done to allow for the human subject to describe his experience by using the robot in a scripted contextual use-case of a potential user scenario. This type of behavioural qualitative testing makes it possible to gain more insights into challenges that arise during use and potential solutions from a user perspective on a hardware level, and software level. By using open-ended and non-leading questions based on observations made during the session, the human subject being interviewed is allowed to reflect on the specific experience to provide valuable feedback for use in future development.

In addition, later after the test session, a user survey is conducted. The Igroup Presence Questionnaire (IPQ) [23] is taken into account. The IPQ test is a scale that assesses the sense of presence experienced in a virtual environment (VE). The IPQ currently has three sub-scales and one additional general item that is not part of a sub-scale. The three sub-scales, which can be regarded as independent factors, include: a) spatial presence - the sense of being physically present in the VE; b) involvement - measuring the attention devoted to the VE and the involvement experienced; c) experienced realism - measuring the subjective experience of realism in the VE. The additional general item assesses the “sense of

(a) (b) (c)

Fig. 5: One of the considered tasks consists of grasping a box from a shelf. The synchronised figures depict (a) the human subject performing the task, (b) the EVEr3 MR application, and (c) the EVEr3 Humanoid Research Robot.

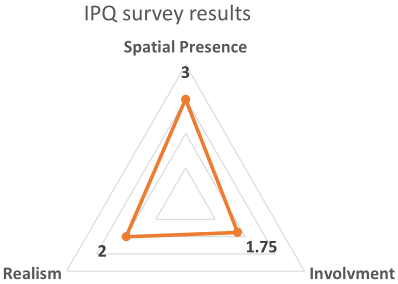

Fig. 6: The IPQ survey results.

being there”, and has high loadings on all three factors, with an especially strong loading on spatial presence.

## V. EXPERIMENTAL RESULTS

Figure 5 depicts the scene of one human subject teleoperating the robot to perform simple grasping, release, and human-robot handover tasks. A video depicting the entire experiment is available on-line at https://youtu.be/vZw1Ne-kB5Y. The IPQ survey results for the multi-modal rendered experience are shown in Figure 6. These results are very promising regarding spatial presence and realism, while involvement is relatively well perceived.

During the qualitative interview, the human subject described common symptoms of cybersickness [24], [25], which mainly involved a sense of nausea and discomfort occurring after prolonged use of the MR headset. The following observations revolved around challenges that the human subject experienced during use, with one core problem being the lack of depth perception and latency issues. Moreover, it was also reported a feeling of being overwhelmed due to an overcrowded user interface on each of the hand controllers. This made certain action difficult to find without being thoroughly familiar with the controller layout. The armrests of the wheelchair were sometimes blocking the view required for tracking movements. This forced the human subject to reset the tracking on a few occasions. Observations made by the test facilitator indicate that this may happen in scenarios where the arms of the robot avatar are placed in the default resting position or at a similar height. Further feedback provided from the human subject was the lack of response from either the user interface when pressing buttons or the absence of feedback from the robot through the head-mounted display at the occurrence of errors that require immediate actions to prevent shutdowns. Lastly, tasks revolving around HRI were considered. In particular, the facilitator participated in human-robot handover tasks similar to a real-world scenario. The operator felt safe and comfortable during these interactions.

## VI. CONCLUSIONS AND FUTURE WORK

This study introduced an innovative mixed reality (MR) enabled teleoperation framework of a humanoid robot for paraplegic patients. A fully immersive visual experience can be achievable thanks to the proposed framework. The EVEr3 Humanoid Research Robot from Halodi Robotics [5] is selected for this purpose, while the Unity gaming engine [6] and the Oculus Rift S [7] controller are used to enhance the patient’s capabilities. A human subject research was performed to validate the developed framework in a home-/workplace setting. According to the collected findings, the considered framework augments patient engagement as well as perception of spatial presence, realism and involvement.

As future work, the possibility of dynamically obtaining a whole-body geometric retargeting [26] to scale the proportion of the robot avatar and personalise it to the human subject could be considered. Moreover, the proposed framework could be complemented by providing the operator with tactile and auditory feedback. This will make it possible to enable a more immersive user experience. This can be accomplished by merging MR tools with novel wearable haptic device created by supplementing low-cost commercial off-the-shelf (COTS) controller with vibrotactile actuators [27]–[30]. Future iterations through a heuristic evaluation should be conducted in future work in the user experience with the user in focus, and their limitations. According to the user feedback, a less overwhelming user interface, better responsiveness, better feedback from user actions, depth perception, and error prevention need to be taken into consideration. Future studies revolving around the human-robot interaction (HRI) should be consecrated where the robot operator and robot are in separate areas. Additionally, a larger pool of human subjects should be recruited in future testing. Finally, the user interface may be improved by preparing feedback for the human subject based on being outside the "comfortable, not overheating" working range and by providing battery charge level and warnings.

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