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# Virtually turning robotic manipulators into worn devices: opening new horizons for wearable assistive robotics

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**Abstract**—Robotic sensorimotor extensions (supernumerary limbs, prosthesis, handheld tools) are worn devices used to interact with the nearby environment, whether to assist the capabilities of impaired users or to enhance the dexterity of industrial operators. Despite numerous mechanical achievements, embedding these robotics devices remains critical due to their weight and discomfort. To emancipate from these mechanical constraints, we propose a new hybrid system using a virtually worn robotic arm in augmented-reality, and a real robotic manipulator servoed on such virtual representation. We aim at bringing an illusion of wearing a robotic system while its weight is fully deported, thinking that this approach could open new horizons for the study of wearable robotics without any intrinsic impairment of the human movement abilities.

A video showing the set-ups and some of their applications can be found on YouTube at: <https://youtu.be/EgwzT784Fws>, and we will be referring to it throughout the paper.

## I. INTRODUCTION

Among wearable robotic devices, robotic sensorimotor extensions are serial augmentations of the human body aiming to increase the user's motor abilities. These devices include but does not limit to prosthesis [1], supernumerary limbs [2] or handheld robotic tools [3]. Despite mechanical advances over the last decades, embedding these robotic devices on the human body remains critical as their weight [4], [5], cumbersomeness and limited functionalities [6] restrain their comfort and acceptance [7], leading many potential users to prefer simple mechanical devices [8] or the use of their natural limbs [9].

In spite of these disadvantages, those wearable devices remain unique: as indicated by their name, they are worn by their user, meaning that, in addition to being transportable, the robot end-effector's transform relative to the world frame  $T_{E_R \rightarrow W}$  can be written as a composition of:

- the robotic control relative to its human attachment base  $T_{E_R \rightarrow E_H}$ ;
- and the movement of the human body relative to the world  $T_{E_H \rightarrow W}$ .

We can rephrase it as: the robot and the human kinematic chains are serially connected. It writes:

$$T_{E_R \rightarrow W} = T_{E_R \rightarrow E_H} T_{E_H \rightarrow W}, \quad (1)$$

where  $T_{A \rightarrow B}$  the transform from frame  $A$  to frame  $B$ ,  $E_R$  the robotic end-effector frame,  $E_H$  the human effector frame to which the robot base is attached, and  $W$  the world frame.

If the human plus the robot system form a kinematically redundant chain (i.e. when the dimension of joint space is greater than the dimension of end-effector space [10]), it also means that the task completion is shared between the human motion  $T_{E_H \rightarrow W}$  and the robotic motion  $T_{E_R \rightarrow E_H}$  (Fig. 1):

- $T_{E_R \rightarrow E_H}$  is usually governed by an auxiliary signal coming from a joystick-like input [11], a sensor system measuring electrophysiological activities (such as muscles activities through EMG [12] or cerebral activities through EEG [13]), or an automatic task-oriented behaviour [14];
- $T_{E_H \rightarrow W}$  depends on the attachment point of the worn device, whether the arm or forearm for an upper-limb prosthesis, the trunk or hips for a supernumerary limb, or the hand for an handheld tool, and of the movements of the user.

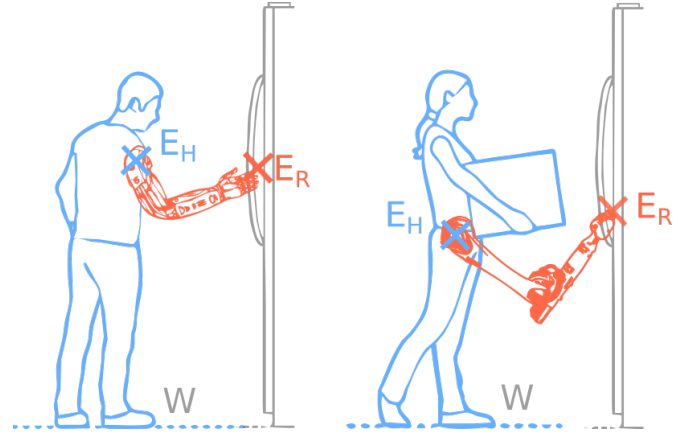


Figure 1: A robotic sensorimotor extension in orange (prosthesis or supernumerary robotic limb) with effector  $E_R$  (orange cross) is attached on an user at  $E_H$  (blue cross), to perform a reaching task.

Yet, this kinematic redundancy is frequently underused, leading to undesirable postures for the user:

- in prosthesis control,  $T_{E_R \rightarrow E_H}$  is piloted by myoelectric activities of the stump and is often slow and non-intuitive leading to important body compensations [15] by  $T_{E_H \rightarrow W}$  over  $T_{E_R \rightarrow E_H}$ ;
- oppositely, in supernumerary robotic limbs, the weight of the robotic device limits the dexterity [16] of  $T_{E_H \rightarrow W}$  (by creating imbalance and fatigue) and imposes the use of  $T_{E_R \rightarrow E_H}$  over  $T_{E_H \rightarrow W}$ .

Currently, the discomfort and limited performances of these devices and of their control still limit the potential of their usage, as the weight of the device is fully carried by the user.

## II. VIRTUALLY TURNING ROBOTIC MANIPULATORS INTO WORN DEVICES

To solve the previous issue, we propose a new set-up which fully deports the weight of the robotic device to a nearby environment, while still keeping a serial connection between the user and the device: we create an augmented-reality representation of an arm, attached to the body frame  $E_H$ , ending with a virtual end-effector frame  $E_{AR}$ , while a robotic manipulator set nearby with an end-effector frame  $E_R$  is servoed to follow  $E_{AR}$  (see Fig. 2 and video Sec. 1):

$$\begin{cases} T_{E_{AR} \rightarrow W} = T_{E_{AR} \rightarrow E_H} T_{E_H \rightarrow W} \\ T_{E_R \rightarrow W}(t) = f(T_{E_{AR} \rightarrow W}(t)) \end{cases} \quad (2)$$

with  $f$  the robot dynamics and control, causing delay when visually servoing the position of robotic end-effector.

The fundamental serial connection of worn robotic devices is now purely virtual, allowing to deport the weight, whereas the real robotic manipulator, physically detached from the human body, performs the desired task with a certain delay (imposed by its dynamics or control loop limitations). By doing so, we aim at virtually creating a sensation of physical embodiment of the deported manipulator.

As said, the robotic manipulator is often slower than the human motions  $T_{E_H \rightarrow W}$ , creating a delay between the virtual frame  $E_{AR}$  motions and the robotic effector  $E_R$  motions. But, by representing the virtual arm in augmented-reality, we partially solve these dynamic issues as we delete the perception delay for the user, tending to more stable motions. This representation is however not necessary for the system to actually work and, with training, can be removed (see video Sec. 4).

Finally,  $T_{E_H \rightarrow W}$  can be generated from any body part  $E_H$ , such as the head, trunk or arm (see video Sec. 2) depending on the user's preference and the applications, while  $T_{E_{AR} \rightarrow E_H}$  can still be controlled by an auxiliary input, like a joystick (see video Sec. 3).

To sum up, the proposed set-up allows to:

- shift the weight and embody any existing robotic system as a virtually worn device, even heavyweight devices, offering the possibility to reach higher robotic performances and higher comfort;
- create mechanically unfeasible limbs, such as an arm attach to the head for disability assistive applications, or a extended third arm with wide workspace for industrial applications;
- instantly attach and detach any robot device to the user's body, switch systems and shift the attach point from one to another for different use-case scenarios, unlike current devices which usually require important preparation times.

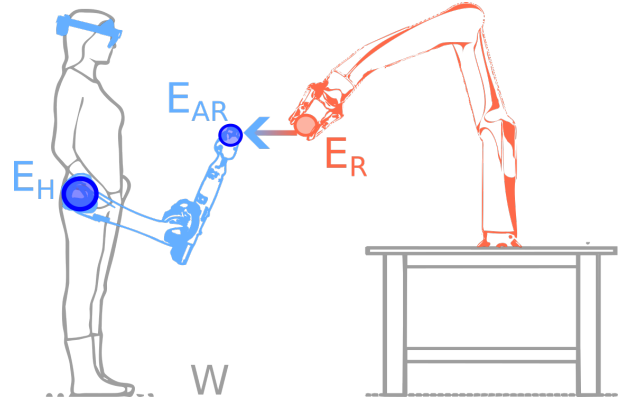


Figure 2: The user (grey) wears a virtual robotic arm in blue at attach point  $E_H$  (blue circle on the user), with virtual end-effector  $E_{AR}$  (blue circle at the end of the robot). The virtual arm made visible thanks to the AR headset in blue on the users' head. Then, the virtual end-effector servoed the effector of a deported robotic arm's (orange circle) set on a table, with a delay depending on the robot dynamics and control (symbolized by the arrow).

## III. PRACTICAL IMPLEMENTATION

### A. Controlled Environment

For research purposes, in controlled and room-sized environments, the easiest and most flexible implementation is to use an optical motion capture system such as the Optitrack system, and an augmented-reality headset like the Microsoft HoloLens V2 for display, as seen Fig. 3.

The motion capture system allows to capture the body transform  $T_{E_H \rightarrow W}$  while easily switching from one body attach point  $E_H$  to another. By putting another marker on the robot end-effector  $E_R$  it also allows to perform visual position servoing. The augmented-reality headset is then only used for display and is actually not necessary to control the robot, rather serving as a visual feedback provider which increases the easiness of use. Finally, another auxiliary control input, such as a joystick, button or electrophysiological system can be added, whether to reconfigure and control the virtual linkage  $T_{E_{AR} \rightarrow E_H}$  or to control a robotic gripper.

### B. Fully wearable set-up for applied scenarios

Optical motion capture systems cannot be worn. However, the Microsoft HoloLens V2 is equipped with a visual 3D slam function which allows to detect at all time the position of the user's head and can be used to calibrate the robot with the headset. By using Inertial Measurement Units on the trunk and the arm, and a simple kinematic model of the user, one can then reconstruct the upper-body joint positions and the transform  $T_{E_H \rightarrow W}$  (see video Sec. 5). Auxiliary inputs measurement can also be implemented in the headset, using its gaze tracker to control the gripper for example.

This measurement system is fully wearable and transportable (the headset being autonomous) and cheaper than the optical motion capture system, but it requires more development and time to be fully operational, as well as previous



Figure 3: The user frame  $E_H$  (blue cube) and robot end-effector frame  $E_R$  are tracked using an Optitrack system. The Microsoft HoloLens V2 headset displays the virtual arm (blue), its virtual effector  $E_{AR}$  (blue octagon) and current robot arm effector configuration (orange cube), represented here. The robot effector is servoed to follow the virtual effector.

knowledge regarding the user's body part to which the virtual robotic arm should be attached.

However, as it can be seen on our setup, a critical aspect of worn robotics which was not resolved here is the transportability of the system, as the robotic manipulator is set on a table. To solve the latter, we could consider to embed the manipulator on a mobile base, wheeled or legged, which could follow the user's motions in a larger environment, or on a wheelchair for assistive applications, and use an inverse kinematic model of both the base and the manipulator to servo the system.

#### IV. CONCLUSION

We proposed a novel approach for robotic extensions, in which the worn device is fully virtual but distantly controls a real robotic manipulator. This allows to virtually embody any high-performance robotic device without weight or embodiment issues, and explore applications that were previously unfeasible — an arm attached to the head or a very long arm fixed to the trunk — without constraining the user's body with heavy and uncomfortable wearable devices. We think that this approach opens new horizons for the study of wearable robotics by fully emancipating from the mechanical constraints of the systems, allowing to explore both fundamental and applied aspects of worn devices without intrinsic impairment of the human motions.

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