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Lightweight and Wearable Mechanical Tracker for Upper Limbs designed for Telemanipulation Tasks

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***Abstract*— This paper introduces a lightweight, wearable device for telemanipulation tasks. Combined with the previously developed Mechanical Hand Tracker (MHT), it enables tracking the position and orientation of each fingertip relative to the torso without relying on grounded systems like calibrated cameras, allowing the user to move freely. The device overcomes common issues associated with data gloves and computer vision methods. We propose a design methodology for a linkage mechanism that maintains full mobility of the upper limbs and fingers while adapting to various body sizes. Teleoperation tests in a pick-and-place scenario were conducted to demonstrate its functionality.**

According to the literature, there are three primary methods for motion-tracking in teleoperation: i) vision-based systems; ii) mechanical tracking systems (such as manipulators or haptic interfaces); and iii) wearable tracking sensors and suits. In this paper, we introduce an Upper Limbs-Tracker, depicted in Fig. 1, designed for precise tracking of the back of the hands in telemanipulation tasks. Vision-based systems can use optical markers or artificial vision, but both face challenges like occlusions and poor lighting conditions (e.g., direct sunlight).

Wearable tracking systems generally rely on inertial measurement units (IMUs) attached to the body to estimate pose, offering portability and independence from stationary sensors. However, they are prone to drift over time due to the integration of sensor data, even after applying filtering and fusion techniques [1], [2].

A different approach is represented by mechanical tracking system. When a robotic device is used as a haptic interface for the user, the position of the end-effector can be obtained from the joint sensors of the device.

This conventional approach is still implemented in current literature for teleoperation of avatar systems, in particular when the implemented interface is a grounded robot, used to render kinesthetic force feedback as well [3]–[5].

A similar approach can be transferred to fully wearable mechanical tracking systems; [6] and [7] proposed prototypes of wearable trackers in the form of exoskeleton links attached to the arm and the forearm.

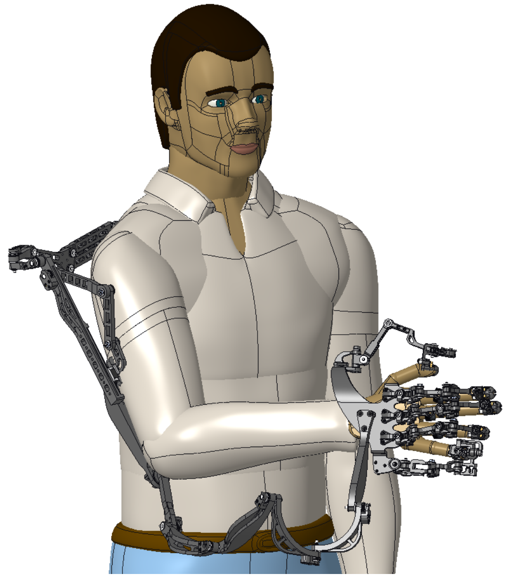

Fig. 1. CAD view of the wearable mechanical upper limbs-tracking system endorsing serial kinematic chains for precise hand dorsum pose estimation.

With a similar paradigm, our MULT system is a passive exo-suit designed for the upper limb, using a serial kinematic chain to track motion. It measures joint rotations to determine the position and orientation (6D pose) of the hand relative to the torso, which serves as the global reference frame. The system uses a real-time kinematic model to calculate the hand's pose based on joint encoder data

Compared to other state-of-the-art wearable systems, MULT offers full upper limb mobility, adaptability to different body sizes, compliance with space constraints, and is both low-cost and lightweight thanks to 3D printing. Additionally, it can incorporate a mechanical hand-tracker we previously developed [8] to enable finger tracking and provide tactile feedback during teleoperation.

I. DESIGN OF THE MECHANICAL TRACKING SYSTEM

A. Kinematic Upper Limb Model

An upper limb model is necessary to design the MULT device (see ahead subsection I-E). In this work, the classical kinematic model proposed in [9] and [10] is adopted. Consequently, a total of 9 DoFs is found from the clavicle to the back of the hand.

Several aspects have been considered, most of all to guarantee general body joint mobility and the ergonomics.

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B. Screw Theory Approach to the Kinematic Design

The goal of the kinematic design is to determine the minimum number of MULT joints/DoFs required to achieve complete upper limb mobility. To accomplish this, the Screw Theory (ST) methodology is employed [11]. A detailed discussion on this approach can be found in our previous work [8]. By applying this theory, MULT does not restrict the wearer's movement as long as each chain between two anchor points maintains a full 6 independent DoFs throughout the user's entire workspace (or range of motion).

C. Principal kinematic joints adopted

For small-scale designs, pin joints are preferable compared to other construction methods, as is commonly recognized in practice [8] and demonstrated again in our previous work [12]. Consequently, all the DoFs in the MULT model were implemented using combinations of pin joints (e.g., a quadrilateral configuration to achieve translational DoF).

D. Working Principle of the Tracker

As said in Sec. I-B, between each anchor point there is a single kinematic chain with 6 independent DoFs, that allows free movement of the wearer's upper limb. A given pose of the limb corresponds to a single pose of the MULT (because of the system composed by MULT and wearer is a Parallel Kinematic Chain). Thus, the pose of the last anchor point can be found based only on the serial kinematic chain defined by the tracker itself.

E. Mechanical Tracker Design

According to the previous considerations, the MULT kinematic has a "branched" structure that deploys from one point on the back with two branches closed on 2 distinct anchor points: one on the homer and one on the hand dorsum. Every branch has 6 independent DoFs and allows the adjustment of the device position, thus improving its wearability. Twelve encoder values allow to solve the direct kinematics and, consequently, to estimate the hand pose.

II. PRELIMINARY EXPERIMENTAL ASSESSMENT

A. Experimental Setup

As an initial functional evaluation, we created an experimental setup, illustrated in Fig. 2, to assess whether the MULT can effectively target the dorsum of the operator's hand for telemanipulation tasks. In this scenario, the operator wears the MULT on their right arm, along with the Mechanical Hand Tracker (MHT) introduced in [8] (right hand). The MHT also serves as a fixed interface for the third branch of the MULT. In addition, MHT is provided by tactile feedback that, as largely discussed in our previous work, it's enough for leading the users to conduct teleoperation tasks precisely, and a force feedback is not necessary. This reason allows to keep lightweight the device. The remote system (follower) is a commercial manipulator, specifically the 7-DoF Franka Emika Panda, arranged in a vertical configuration to emulate the human arm. The Panda's end-effector is equipped with the CORA Hand [13].

Fig. 2. Experimental setup arranged for a pick-and-place telemanipulation scenario.

B. Telemanipulation Test

After a first proof where we verified that the MULT prototype allows full mobility of the upper limb in the entire user's workspace, comprising singularity configurations, the main validation experiment consisted of the pick-and-place of a water bottle. The experimental procedures were approved by the Ethical Review Board of Scuola Superiore Sant'Anna (approval number 152021). The operation requires picking the bottle from the table, moving it away from the table edge, and then placing it back on the table in the same original position (as shown in 2).

C. Discussion on a Qualitative Evaluation

Throughout the pick-and-place test, the participant made only a few errors, largely due to imperfections in the prototype that affected tracking precision. The first prototype's mechanical construction used rapid-prototyping plastic links, which, due to lower stiffness, impacted the orientation and alignment of certain joints. As a result, the actual degrees of freedom (DoFs) may have deviated from the intended kinematics. Additionally, the use of dry-friction bearings in the pin joints introduced mechanical backlash, necessary for movement but also causing slight misalignments that affected the overall hand pose estimation.

III. CONCLUSIONS AND FUTURE WORK

The mechanical tracking approach is well-suited for teleoperation, offering robust performance against occlusions and environmental challenges. Our device is designed to adapt to the user's body and cover the full range of upper limb motion, using screw theory for an adaptive kinematic design. The prototype, equipped with wireless electronics, was tested in a teleoperation setup, including static assessments and a pick-and-place task with a robotic arm and hand. Initial results confirm the prototype's effectiveness, with future tests planned for more complex manipulation scenarios leveraging its wide coverage and occlusion resistance.

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