Feeling Good: Validation of Bilateral Tactile Telemanipulation for a Dexterous Robot

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Abstract. We introduce a novel bilateral tactile telemanipulation system for dexterous robots. The system is based on a leader-follower paradigm: it integrates two leader devices, a 6D manipulandum and a 3-finger exoskeleton, which allow the human operator to directly control a robot arm and dexterous robot hand simultaneously on the follower side. Tactile sensors are mounted on the four fingertips of the robot hand to collect contact data during remote object manipulation and surface exploration; the measured tactile information is translated into haptic feedback on the leader side, enhancing the performance of the human operator by increasing transparency and reducing physical and mental fatigue during teleoperation. Thanks to its rich haptic feedback, the system is particularly interesting for blind teleoperation, where visual feedback of the workspace is not available or is limited and of poor quality, as for example in the exploration of spaces with reduced illumination and in the manipulation of objects in presence of occlusions. We report the outcomes of preliminary validation experiments, which demonstrate the effectiveness of the control methodology and provide evidence supporting the feasibility of our approach.

Keywords: Teleoperation · Robotics · Tactile Sensing · Haptic Feedback · Robotics Manipulation.

1 Introduction

Although the interest and effectiveness of robot teleoperation have been widely acknowledged [1, 2], various technological and cost barriers have hindered research in this field, leaving many aspects unexplored. The vast bulk of research on the topic has focused on the use of artificial or human visual feedback, which has led to advancements in transparency (i.e. the ease with which one can cognitively accept a robotic arm as an extension of their own body) and dexterity in completing increasingly challenging tasks [3].

However, in recent years, significant progress has been made in the design of new tactile sensors [4], and in the development of computational techniques to extract relevant information from them during robotic manipulation and exploration [5], either in isolation of combined with visual sensing [6]. As a result, it is no longer rare to find tactile sensors used as the end effector tips of robotic arms, particularly during remote teleoperation experiences [1, 7]. The prospect of combining these two technological systems along with the advancements of virtual reality [8] and wearable haptic systems [9] is driving the development and integration of devices that provide, during teleoperation, the human-operator with a sense of physical contact with remotely controlled items through haptic feedback. Although the idea is not new [10], the recent technological advancements have proven that this could be the way forward for robotic teleoperation [11, 12]. Our work introduces a new tactile telerobotic setup, shown in Fig. 1, that enables fluent and effective teleoperation based on the integration of a 6D arm manipulandum with force feedback, a hand exoscheleton with force feedback, a remote robotic manipulator with a four-finger tactile hand and a virtual reality headset for visualisation of the remote environment.

Through this setup, we can record relevant aspects of the human motion and manipulation strategies, to effectively control the actions of the robotic follower, and provide feedback to the human operator for enhanced immersion in the task; additionally, valuable data about the manipulated objects can be extracted by the follower robot. Notably, the rich contact information that we gather from the follower side and we render on the operator through the leader device can either complement or completely replace visual information. The challenge of limited camera installation options or low data transmission capacities is a significant obstacle to the optimal performance and consistency of teleoperation systems. Moreover, cameras are often unable to capture images effectively under varying lighting conditions, which highlights the importance of developing effective solutions to overcome these challenges and enhance the reliability and effectiveness of teleoperation systems [13]. For this reason, a further motivation for building such a sophisticated robotic setup is to enable blind teleoperated exploration and manipulation [14], where rich haptic feedback generated solely from contact information is crucial.

We believe that this setup paves the way for a number of studies and applications, such as the digital reconstruction or classification of objects, assessing the behaviour of the human operator in performing complex activities in cooperation with a robot, and learning from the human demonstration a control policy that enables the robot to autonomously perform exploration and manipulation tasks, also in challenging environments.

The aim of this preliminary study is to evaluate the reliability of our advanced teleoperation system by conducting a sponge brick pick-and-place task. During this pilot experiment, the operator perceives, via an exoskeleton glove, feedback of contact forces that are measured through tactile sensors mounted on the fingertips of the robot and conveyed as kinesthetic haptic feedback. The Results section (3.2) presents separate analyses of the teleoperation of the end effector, the finger control, and the haptic feedback experienced by the operator.

2 Telemanipulation System

The robotic telemanipulation setup depicted in Fig. 1 has been designed to offer a configuration that is as human-centric and natural as possible for everyday handling scenarios. The follower side robot (UR5 robot arm and Allegro robot hand with custom tactile fingertips) is mounted on a custom-made vertical stand, known as MARIA (the Queen Mary multi-arm robot interactive assistant), to approximately mimic the positioning of the human arm on the torso. The leader side device (Virtuose 6D arm manipulandum [15] with HGlove hand exoschele-ton [16]) has been positioned to have an operating height that is compatible with the natural arm posture of a standing human adult, offering a wide range of motion to effectively telemanipulate objects placed on a tabletop in front of the follower robot. This setup is an extension of a previous setup that featured a more limited tactile feedback from the robot hand fingertips, and a simpler and cheaper leader device composed of a Leap Motion controller for hand tracking and a custom data glove for vibro-tactile feedback [17, 18]; the setup was tested on telemanipulation tasks [19], demonstrating that the simple tactile feedback already reduced cognitive load, as compared to no feedback [20]. Although we did not formally compare these two setups in terms of cognitive load and task performance, we believe the current setup is even more natural and effective, based on our daily experience in the lab. The following subsections provide a detailed explanation of the devices and control strategies employed. The Robot Operating System (ROS) is utilized as the middle-ware interface for communication and control.

2.1 Human-Operator's Leader Interface

On the leader side, a combination of Virtuose 6D and HGlove [16] is used to track the position of the hand of the operator in Cartesian space and the bending of each of the fingers. In particular, Virtuose 6D is able to provide the pose of the wrist and relying on an impedance controller it is possible to generate haptic feedback on the arm of the operator. This can be used to mimic the force sensed on the follower side including the weight of the grasped object, or simply to compensate for the weight of the exoskeleton. This latter feature is crucial in reducing the muscular effort of the user during prolonged teleoperation. Additionally, it is possible to create a software-implemented constraint known as a forbidden region haptic virtual feature [21] that prevents the operator from teleoperating the follower robot in that area. Fig. 1 exhibits a light blue box encompassing the non-forbidden region.

Furthermore, the movement of the fingers of the operator in the joint space can be tracked using HGlove, an exoskeleton glove. It provides a measure of the distal, proximal, and lateral movements of each of the three fingers, namely the thumb, index, and middle. Additionally, HGlove has actuators which produce kinesthetic haptic feedback for each finger on the distal and proximal joints.

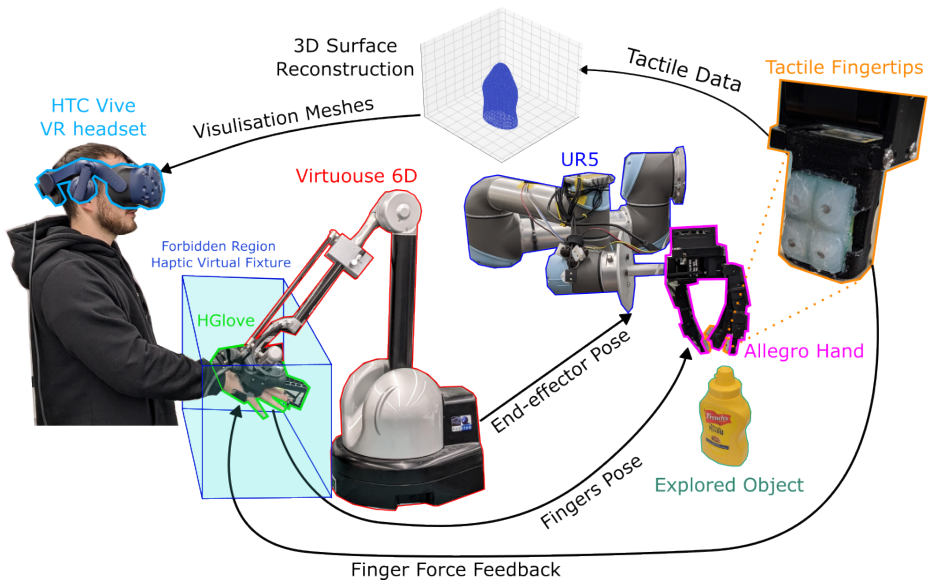

Fig. 1. Control Scheme for Bilateral Teleoperation: the end effector pose of the UR5 is controlled by the operator using Virtuose 6D while the finger movement of the Allegro Hand is controlled using HGlove. Beyond the blue box, a forbidden movement region is enforced using a haptic virtual fixture that prevents the operator from teleoperating the robot past it. Information regarding contact forces is gathered from the custom tactile sensors mounted on the fingertips of the robotic hand and used to create haptic feedback using Hglove as well as to digitally reconstruct the shape of the explored object in real-time. Finally, visualization meshes can be streamed to the operator through a display apparatus to improve the transparency of teleoperation.

2.2 Robotic Manipulator Follower

For the follower side, a combination of UR5, Allegro Hand, consisting of four fingers, and customised tactile sensors [22] is proposed. To match the information received from Virtuose 6D, we found it convenient to proceed to work in Cartesian space. For this reason, we used RelaxedIK [23] as an optimiser to compute the inverse kinematics of UR5 that prevents self-collision. On the other hand, for finger control, we identified a reasonable empirical mapping to transfer information from the finger joint space of the HGlove to the finger joint space of the Allegro Hand. To ensure that this mapping remains consistent, HGlove is software-calibrated for each use to align each user's open/closed hand with the corresponding Allegro Hand configuration.

In the design of the Allegro Hand fingertips, we made the decision to customize our sensors to provide more flexibility in terms of the forces sensed as well as the shape that would be most convenient for manipulation experiments. We based our model on previous work, specifically the uSkin model[24, 25], although reducing the number of sensitive taxels on each fingertip to reduce the overall size and complexity, inspired by recent work [22].

Using these tactile sensors, it is possible to estimate an averaged normal force on the four contact points from each fingertip, which can be used as force feedback to generate kinesthetic haptic feedback on the hand. Moreover, the shear forces information is crucial to obtain valuable information about the objects and about the physical interaction between the robot and the object during manipulation, that can help to recognize grasped objects [26] and to detect slip [27].

2.3 Teleoperation Architecture

The control architecture includes three components: Cartesian Tracking of the robot end-effector pose; joints control of the Allegro hand; Haptic feedback. the first domain pertains to the teleoperation of the desired pose of UR5 end effector in the Cartesian space, $\hat{\mathbf{P}}_{\mathrm{UR5}}(t)$, while the second domain relates to the teleoperation of the Allegro Hand fingers using joint space control. Finally, a rule is required to render the forces measured by the sensors as haptic feedback on the fingers of the operator.

Cartesian Tracking. We define the pose of the end-effector (of either the Leader or the Follower robot arm) as a vector, $\mathbf{P} = [\mathbf{p} \;\; \mathbf{q}]^{\mathbf{T}}$, containing the Cartesian position $\mathbf{p} = [\mathbf{x} \;\; \mathbf{y} \;\; \mathbf{z}]$ and the quaternion orientation $\mathbf{q} = [\mathbf{q_x} \;\; \mathbf{q_y} \;\; \mathbf{q_z} \;\; \mathbf{q_w}]$. We define a control variable, $\Delta\mathbf{P}_{\mathrm{virt}}(t) = \mathbf{P}_{\mathrm{virt}}(t) - \mathbf{P}_{\mathrm{virt}}(t_0)$, which is the difference between the initial pose and current pose of the end-effector of the Leader robot. The control variable is mapped to a desired displacement of the end-effector of the Follower robot, $\hat{\mathbf{P}}_{\mathrm{UR5}}(t) = \mathbf{P}_{\mathrm{UR5}}(t_0) + \Delta\mathbf{P}_{\mathrm{virt}}(t)$.

Ultimately, the desired displacement of the joints of the Follower robot, $\hat{\theta}_{\mathrm{UR5}}(t) = \mathbf{RelaxedIK}(\hat{\mathbf{P}}_{\mathrm{UR5}}(t))$, is obtained through inverse kinematics computation, using the RelaxedIK solver [23], an optimizer that has demonstrated robustness for real-time teleoperation and that avoids self-collision between the robot joints.

Joints Control of the Allegro Hand. Concerning the control of the Allegro Hand joints, $\boldsymbol{\theta}^{\boldsymbol{Allegro}} = \left[\theta^{\mathrm{in}} \;\; \theta^{\mathrm{mid}} \;\; \theta^{\mathrm{ring}} \;\; \theta^{\mathrm{th}}\right]^{\top} = [\theta_0 \;\; \theta_1 \ldots \theta_{15}]$, an arbitrary mapping, $\hat{\boldsymbol{\theta}}_{\mathrm{i}}^{finger}(t) = \boldsymbol{\theta}_i^{finger}(t_0) + \Delta\boldsymbol{\gamma}_j^{finger}\alpha_i^{finger}, i, j \in \{0, 1, 2, 3\}$, between the joint space of the two devices was established. To this end, a variable $\Delta\gamma(t) = \gamma^{\mathrm{HG}}(t) - \gamma^{\mathrm{HG}}(t_0)$, where $\boldsymbol{\gamma}^{\boldsymbol{HG}} = [\gamma^{\mathrm{in}} \;\; \gamma^{\mathrm{in}} \;\; \gamma^{\mathrm{mid}} \;\; \gamma^{\mathrm{th}}]^T$ and $\boldsymbol{\gamma}^{\boldsymbol{in}} = [\gamma_0 \;\; \gamma_1 \;\; \gamma_1 \;\; \gamma_2]^T$, was chosen to represent the angular deviation between the initial and current joint states of each of the fingers of HGlove. In our opinion, this choice partially addresses the vast problem of accurately mapping an exoskeleton with a robotic hand, but we opted for this strategy because we reckon that mapping in joint space is competent for power grasp tasks [28].

The main challenge of the mapping is that HGlove is composed of three joints for each finger while Allegro Hand has four. The same is also true for the number of fingers, as HGlove is composed of three fingers while Allegro Hand has four. For this reason, as illustrated in Fig. 2, we have defined a coupling as follows: the movement of the HGlove thumb controls the thumb of Allegro Hand, the movement of the index finger of HGlove simultaneously controls the index and middle finger of Allegro Hand, and finally, the movement of the middle finger of HGlove controls the movement of the ring finger of Allegro Hand.

Although having under-dimensioned finger actuators on HGlove provides an intrinsic limitation in controlling the higher-dimensional joints of the Allegro Hand, this decision has no impact on the way the operator manipulates, in fact as anticipated, the control of the fingers of the follower is defined by a unidirectional mapping between the leader and the follower. To this end, an empirical calibration of the coefficients within the aforementioned vector $\boldsymbol{\alpha}$, was conducted. This calibration aimed to enable the Allegro Hand to accurately mimic the finger flexion of the hand of the operator, ensuring a realistic and consistent replication. The calibration was executed to ensure that the robotic fingertips grasped objects specifically on the region equipped with sensors.

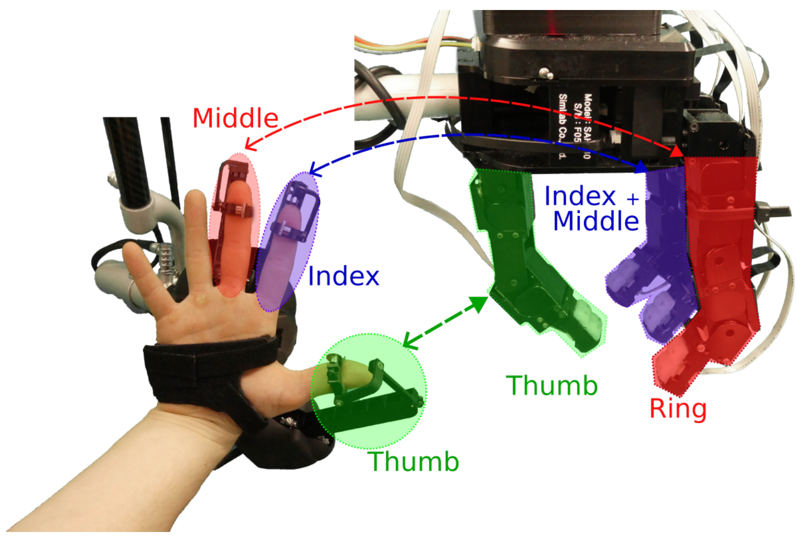

Fig. 2. Mapping of HGlove movement to Allegro Hand. The thumb of the Allegro Hand is controlled by the thumb of the Hglove (green). The index of the HGlove is coupled with the index and middle fingers of the Allegro Hand (blue). Finally, the ring finger of the Allegro Hand is paired with the middle finger of the HGlove (red).

Haptic feedback. Each of the tactile sensors mounted on the fingertips of the Allegro Hand is capable of measuring a 3D vector consisting of both shear and normal force components at four distinct points on the fingertip. While this data would prove valuable for contact analysis during manipulation, it is too voluminous to be utilized for rendering force feedback via the HGlove. To address this issue, the decision was made to use only the highest normal force value measured by each fingertip sensor, as detailed in Eq. (1). Additionally, we set a minimum threshold to distinguish disturbance caused by external magnetic fields on the sensors from a tactile force.

$$F_{\mathrm{z}}^{\mathrm{finger}} = \begin{cases} \max\{F_{z1}, F_{z2}, F_{z3}, F_{z4}\} & \textbf{if } \max\{\dots\} \geq \textbf{threshold} \\ 0 & \textbf{otherwise} \end{cases} \tag{1}$$

Finally, we set a maximum value measured by the sensors, above which haptic force saturates at a maximum limit to ensure the safety of the operator.

3 Experimental Validation

3.1 Methods.

The present study features a telemanipulation experiment which has been recorded and analyzed. The experiment consists of several distinct stages, as depicted in Fig. 3, including (b) approaching the object, (c) grasping the object, (d) moving the object on a surface of varying height, and (e) releasing the object. Through this basic experiment, the key functionalities of our setup are demonstrated, including the capability to navigate the scene, the ability to grasp, manipulate and carry objects, and the ability to render haptic feedback on the hand of the user.

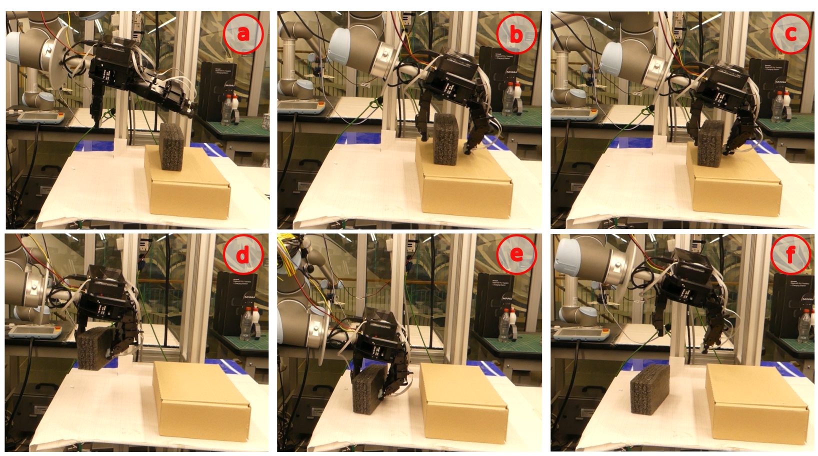

Fig. 3. Teleoperation experiment: pick and place a brick sponge. In (a & f) are shown the starting and final positions. In (b) the approach to the object is shown. In (c) the grasping of the object begins. In (d) the object is transported to a new location at a different height. In (e) the object is placed in the newly reached location.

3.2 Results

End-effector tracking. Fig. 4 shows the trajectories in Cartesian space of the wrist of the operator connected to Virtuose 6D via HGlove and the trajectory of the end effector of the UR5 corresponding to the wrist of the UR5. The graph indicates that the robot is capable of accurately following the operator's movements. However, certain crucial aspects of the experiment require careful consideration. The z-axis trajectory reveals that the robot did not precisely mimic the operator's movement within a particular time interval. This deviation is attributable to a constraint that we imposed on the joint velocity of the robot to prevent hazardous movements; in fact, the discrepancy is observed when the movement speed of the operator increases rapidly. On the contrary, the discrepancy that can be observed on the x-axis trajectory is caused by the simultaneous data recording we perform during the experiment, which increases the computational effort and generates some packet loss in the control communication. Therefore, we have recently modified the data recording strategy to alleviate this problem, which in fact we have now solved (although not reported in this paper).

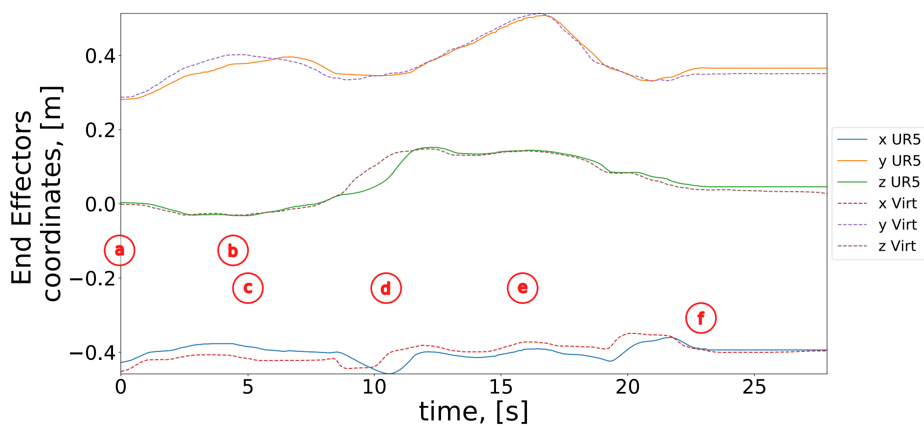

Fig. 4. Wrists trajectories in 3D Cartesian Space. The plot is labelled to emphasize the instances of pick-and-place actions depicted in Fig. 3

Controlling the hand. The left side of Fig. 5 illustrates the angular changes of the joints of the HGLove used to control the corresponding joints of the Allegro Hand, in accordance with the coupling presented in Fig. 2. As discussed in Section 2.3, an empirical mapping was developed to simulate the control of the fingers of the operator, allowing for a mapping from a three-joint space of HGlove to a four-joint space on the Allegro Hand. As shown by the results, the majority of the motion corresponds to the movement of the proximal joint of both devices, which are calibrated in direct proportion to one another. Furthermore, the trajectories for all fingers, with the exception of the thumb, are comparable, as depicted in the graph. Conversely, it was determined to place a greater emphasis on the distal displacement of the thumb.

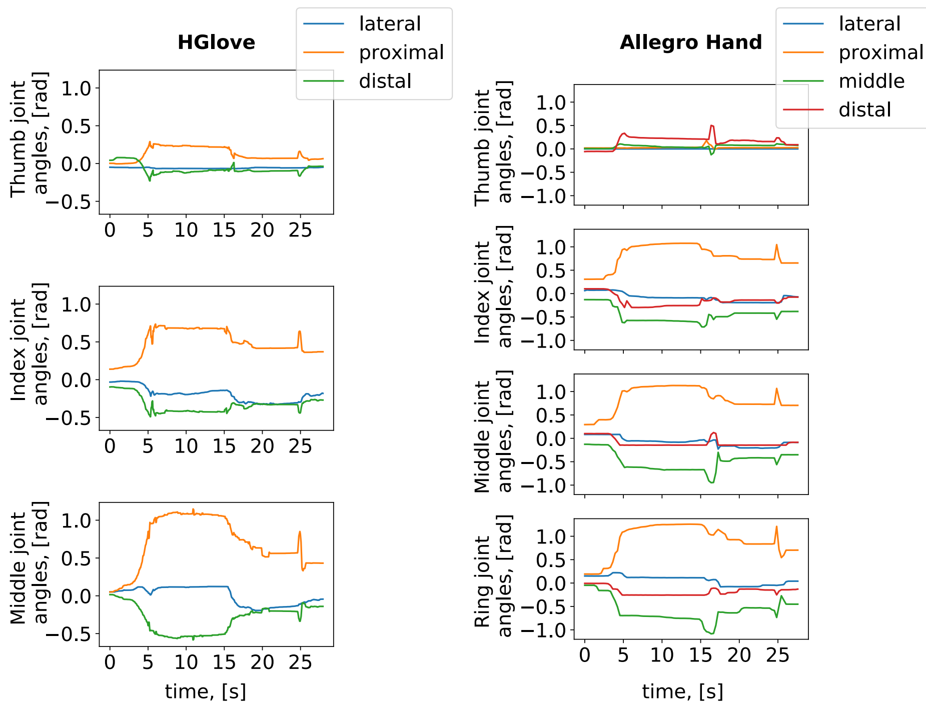

Fig. 5. Fingers Teleoperation Trajectories: The left panel shows the angular joint displacements recorded on the three fingers of the Leader exoskeleton glove, HGlove. The right panel shows the corresponding displacements observed during the pick-and-place task performed by the four fingers of the Follower robotic hand, Allegro Hand. Notably, the middle and ring fingers of the Allegro Hand were jointly controlled by only the middle finger of the Leader.

Haptic experience. The tactile intensities measured by the tactile sensors for each fingers couple during handling are depicted in Fig. 6. While manufactured sensors are prone to disturbances due to external magnetic fields (that can lead even to negative values), the pressure exerted during manipulation generally exceeds the magnitude of such disturbances. Thus, the values obtained have been partially filtered, precluding the possibility of defining a standard unit of measurement. Nevertheless, this data proves to be highly effective in rendering exceptional haptic feedback to the operator, as evidenced by Fig. 6. Whenever a touch with a tactile intensity value higher than 30 is detected by the sensor, a feedback signal proportional to the measured touch is conveyed to the operator as kinesthetic haptic feedback. In this particular case, to render all the values greater than 200 measured by the tactile sensors a maximum force threshold of 5N was established, a value deemed safe to be rendered to the fingers of the operator [16].

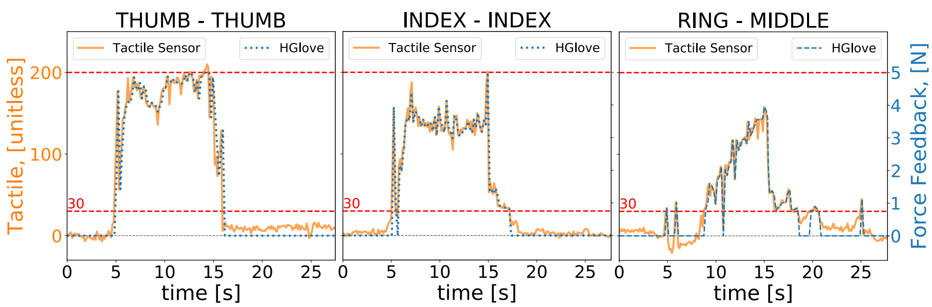

Fig. 6. The plots show haptic sensor measurements (orange) for each of the fingers used to render haptic kinesthetic feedback (blue) on the coupled fingers of the exoskeleton glove. For measurements below 30, haptic feedback is null. Conversely, it is proportional to sensor measurements up to the maximum value of 5N, which is a safe value for rendering all measurements above the threshold of 200.

4 Conclusion and Future Work

In this paper, we introduce a novel tactile telemanipulation setup, in which tactile information extracted from the fingertips of a dexterous robot hand is used to generate force feedback on the human operator during remote object manipulation. The bilateral Leader-Follower control architecture is described in detail, with a focus on the haptic experience. We report the results of preliminary validation experiments that support the feasibility of our sensing, control and feedback approaches.

In previous work, we showed how remote visual sensing can be used in combination with Virtual Reality headsets to feedback to the human operator a detailed 3D reconstruction of the remote environment during telemanipulation, improving task performance and reducing cognitive load [8]. With this novel setup, we believe that similar results could be achieved without having to rely on visual sensing, but solely using tactile sensing, extending previous research on teleoperated [7] and autonomous [29, 22] robotic tactile exploration and 3D reconstruction; this would enable new application scenarios, where visual sensing is particularly challenging due to difficult lighting conditions and considerable occlusions, such as deep sea and space exploration. In addition, we believe that this setup (or, similar systems inspired by the proposed architecture) can be a powerful asset in human studies, to shed more light on the human strategies underlying physical human-robot interaction, and in robot dexterity learning from human demonstrations.

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References

1. K. Darvish, L. Penco, J. Ramos, R. Cisneros, J. Pratt, E. Yoshida, S. Ivaldi, and D. Pucci, "Teleoperation of humanoid robots: A survey," *IEEE Trans. Robot.*, 2023.
2. I. Vitanov, I. Farkhatdinov, B. Denoun, F. Palermo, A. Otaran, J. Brown, B. Omarali, T. Abrar, M. Hansard, C. Oh *et al.*, "A suite of robotic solutions for nuclear waste decommissioning," *Robotics*, vol. 10, no. 4, p. 112, 2021.
3. A. Handa, K. Van Wyk, W. Yang, J. Liang, Y.-W. Chao, Q. Wan, S. Birchfield, N. Ratliff, and D. Fox, "Dexpilot: Vision-based teleoperation of dexterous robotic hand-arm system," in *IEEE ICRA*. 2020, pp. 9164–9170.
4. C. Chi, X. Sun, N. Xue, T. Li, and C. Liu, "Recent progress in technologies for tactile sensors," *Sensors*, vol. 18, no. 4, p. 948, 2018.
5. Q. Li, O. Kroemer, Z. Su, F. F. Veiga, M. Kaboli, and H. J. Ritter, "A review of tactile information: Perception and action through touch," *IEEE Trans. Robot.*, vol. 36, no. 6, pp. 1619–1634, 2020.
6. N. Navarro-Guerrero, S. Toprak, J. Josifovski, and L. Jamone, "Visuo-haptic object perception for robots: an overview," *Autonomous Robots*, vol. 47, no. 4, 2023.
7. B. Omarali, F. Palermo, K. Althoefer, M. Valle, and I. Farkhatdinov, "Tactile classification of object materials for virtual reality based robot teleoperation," in *IEEE ICRA*, 2022.
8. B. Omarali, B. Denoun, K. Althoefer, L. Jamone, M. Valle, and I. Farkhatdinov, "Virtual reality based telerobotics framework with depth cameras," in *IEEE Int. Conf. on Robot and Human Interactive Comm.*, 2020.
9. M. Ogrinc, I. Farkhatdinov, R. Walker, and E. Burdet, "Sensory integration of apparent motion speed and vibration magnitude," *IEEE Trans. Haptics*, 2017.
10. R. Browse and M. McDonald, "Using tactile information in telerobotics," *IEEE Trans. Syst. Man Cybern. Syst.*, vol. 22, no. 5, 1992.
11. J. A. Fishel, T. Oliver, M. Eichermueller, G. Barbieri, E. Fowler, T. Hartikainen, L. Moss, and R. Walker, "Tactile telerobots for dull, dirty, dangerous, and inaccessible tasks," in *IEEE ICRA*, 2020.
12. Y. Liu, Y.-Y. Tsai, B. Huang, and J. Guo, "Virtual reality based tactile sensing enhancements for bilateral teleoperation system with in-hand manipulation," *IEEE Robotics and Automation Letters*, vol. 7, no. 3, pp. 6998–7005, 2022.
13. H. Dang, J. Weisz, and P. K. Allen, "Blind grasping: Stable robotic grasping using tactile feedback and hand kinematics," in *2011 IEEE International Conference on Robotics and Automation*, 2011, pp. 5917–5922.

14. S. J. Lederman and R. L. Klatzky, "Hand movements: A window into haptic object recognition," *Cognitive psychology*, vol. 19, no. 3, pp. 342–368, 1987.
15. J. Perret, "Haptic trends by haption: larger, stronger, faster," in *EuroHaptics Conference*, 2014.
16. J. Perret, Q. Parent, and B. Giudicelli, "Hglove: A wearable force-feedback device for the hand," in *14th annual EuroVR conference*, 2017.
17. B. Junput, X. Wei, and L. Jamone, "Feel it on your fingers: Dataglove with vibrotactile feedback for virtual reality and telerobotics," in *Towards Autonomous Robotic Systems: TAROS.* Springer, 2019.
18. B. Junput, I. Farkhatdinov, and L. Jamone, "Touch it, rub it, feel it! haptic rendering of physical textures with a low cost wearable system," in *Towards Autonomous Robotic Systems: TAROS.* Springer, 2020.
19. C. Coppola and L. Jamone, "Master of puppets: Multi-modal robot activity segmentation from teleoperated demonstrations," in *IEEE Int. Conf. on Development and Learning (ICDL)*, 2022.
20. C. Coppola, G. Solak, and L. Jamone, "An affordable system for the teleoperation of dexterous robotic hands using leap motion hand tracking and vibrotactile feedback," in *IEEE Int. Conf. on Robot and Human Interactive Comm.*, 2022.
21. J. J. Abbott and A. M. Okamura, "Stable forbidden-region virtual fixtures for bilateral telemanipulation," *J. Dyn. Syst. Meas. Control Trans. ASME*, 2006.
22. A. A. Bonzini, L. Seminara, S. Macciò, A. Carfı, and L. Jamone, "Leveraging symmetry detection to speed up haptic object exploration in robots," in *2022 IEEE Int. Conf. on Development and Learning (ICDL)*, 2022.
23. D. Rakita, B. Mutlu, and M. Gleicher, "Relaxedik: Real-time synthesis of accurate and feasible robot arm motion." in *Robotics: Science and Systems*, 2018.
24. T. P. Tomo, A. Schmitz, W. K. Wong, H. Kristanto, S. Somlor, J. Hwang, L. Jamone, and S. Sugano, "Covering a robot fingertip with uskin: A soft electronic skin with distributed 3-axis force sensitive elements for robot hands," *IEEE Robotics and Automation Letters*, vol. 3, no. 1, pp. 124–131, 2017.
25. T. P. Tomo, M. Regoli, A. Schmitz, L. Natale, H. Kristanto, S. Somlor, L. Jamone, G. Metta, and S. Sugano, "A new silicone structure for uskin—a soft, distributed, digital 3-axis skin sensor and its integration on the humanoid robot icub," *IEEE Robotics and Automation Letters*, vol. 3, no. 3, pp. 2584–2591, 2018.
26. E. Kirby, R. Zenha, and L. Jamone, "Comparing single touch to dynamic exploratory procedures for robotic tactile object recognition," *IEEE Robotics and Automation Letters*, vol. 7, no. 2, pp. 4252–4258, 2022.
27. R. Zenha, B. Denoun, C. Coppola, and L. Jamone, "Tactile slip detection in the wild leveraging distributed sensing of both normal and shear forces," in *2021 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, 2021.
28. R. Li, H. Wang, and Z. Liu, "Survey on mapping human hand motion to robotic hands for teleoperation," *IEEE Trans Circuits Syst Video Technol*, 2022.
29. A. A. Bonzini, L. Seminara, and L. Jamone, "Improving haptic exploration of object shape by discovering symmetries," in *2022 International Conference on Robotics and Automation (ICRA).* IEEE, 2022, pp. 5821–5827.