TelePhysicalOperation: Remote Robot Control Based on a Virtual "Marionette" Type Interaction Interface

Article *in* IEEE Robotics and Automation Letters · January 2022

DOI: 10.1109/LRA.2022.3144792

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TelePhysicalOperation: Remote Robot Control Based on a Virtual "Marionette" Type Interaction Interface

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Abstract—**Teleoperation permits to control robots from a safe distance while performing tasks in a remote environment. Kinematic differences between the input device and the remotely controlled manipulator or the existence of redundancy in the remote robot may pose challenges in moving intuitively the remote robot as desired by the human operator. Motivated by the above challenges, this work introduces TelePhysicalOperation, a novel teleoperation concept, which relies on a virtual physical interaction interface between the human operator and the remote robot in a manner that is equivalent to a "Marionette" based interaction interface. With the proposed approach, the user can virtually "interact" with the remote robot, through the application of virtual forces, which are generated by the operator tracking system and can be then selectively applied to any body part of the remote robot along its kinematic chain. This leads to the remote robot generating motions that comply with the applied virtual forces, thanks to the underlying control architecture. The proposed method permits to command the robot from a distance by exploring the intuitiveness of the "Marionette" based physical interaction with the robot in a virtual/remote manner. The details of the proposed approach are introduced and its effectiveness is demonstrated through a number of experimental trials executed on the CENTAURO, a hybrid leg-wheel platform with an anthropomorphic upper body.**

Index Terms—**Human-Robot collaboration, physical Human-Robot interaction, telerobotics and teleoperation.**

I. INTRODUCTION

ROBOTIC teleoperation is one of the oldest fields in robotics [1], but yet an active and evolving research topic finding application in very diverse domains like disaster response [2], surface finishing [3], construction industry [4] and many others, for permitting the remote command and execution of complex loco-manipulation tasks. At the same time, the improved capabilities demonstrated by the recent mobile/legged manipulation platforms have increased the complexity of remotely commanding them, hence augmenting the burden of the operator in executing remote tasks. This has motivated robotics research towards the development of autonomous capabilities as well as more intuitive interaction and command interfaces between the human operator and the remotely operated robot.

Concerning the interaction interfaces, devices with similar [5] or dissimilar [6] kinematics have been exploited with the cons of these approaches being the necessity to design specific slave devices and/or having the operator loaded with a cumbersome interface. Flexible and lightweight interfaces that attempt to track multiple operator inputs have also been explored, based on Inertial Measurement Unit (IMU) devices to direct teleoperate robots [7]–[9]. In this case, the complexity of the slave robot is handled by sending multiple inputs provided by a sensorized body interface. The work in [10] exploits a full body IMU-based suit combined with a human center of pressure model and a tele-impedance interface to control the locomotion and manipulation actions. Tele-impedance control enriches the command sent to the remote robot by combing the masters estimated position and the stiffness references obtained through an Electromyography (EMG) interface [11]. EMG-based Human Robot Interfaces have also been used in [12] to obtain the inputs of the human operator. Instead, the work in [13] combines a motion tracking interface with an autonomous impedance regulator module to deal with the physical interaction uncertainties and task payload conditions of the remote robot.

Despite all the provided solutions, an alternative and very intuitive way to guide the robot is by physically interacting with the robot body to drive it along the desired motion in order to teach it how to execute a desired task. Indeed, physical Human Robot Interaction (pHRI) can assist the operator in accomplishing a task in collaboration with the robot [14], [15]. In [16], a physically interactive control scheme is exploited to permit the operator to touch the robot and to apply forces to make it follow the desired motions. In [17], a direct physical contact between the human and the robot is studied for a series of assembly cooperative task, alternating passive and active robot behaviors to reduce the operator workload and the risk of injuries. Physical interactions have also been explored for mobile robots, like in [18], where the *MObile Collaborative*

Manuscript received September 9, 2021; accepted January 2, 2022; date of current version January 28, 2022. This letter was recommended for publication by Associate Editor Thomas Hulin and Editor Prof. Jee-Hwan Ryu upon evaluation of the reviewers' comments. This work was supported in part by the European Union's Horizon 2020 programme under Grant Agreement Number 101016007 CONCERT and in part by the Italian Fondo per la Crescita Sostenibile - Sportello Fabbrica intelligente, PON I&C 2014 - 2020 under Project F/190042/01-03/X44 RELAX. *(Corresponding author: Davide Torielli).*

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This letter has supplementary downloadable material available at https://doi.org/10.1109/LRA.2022.3144792, provided by the authors.

Digital Object Identifier 10.1109/LRA.2022.3144792

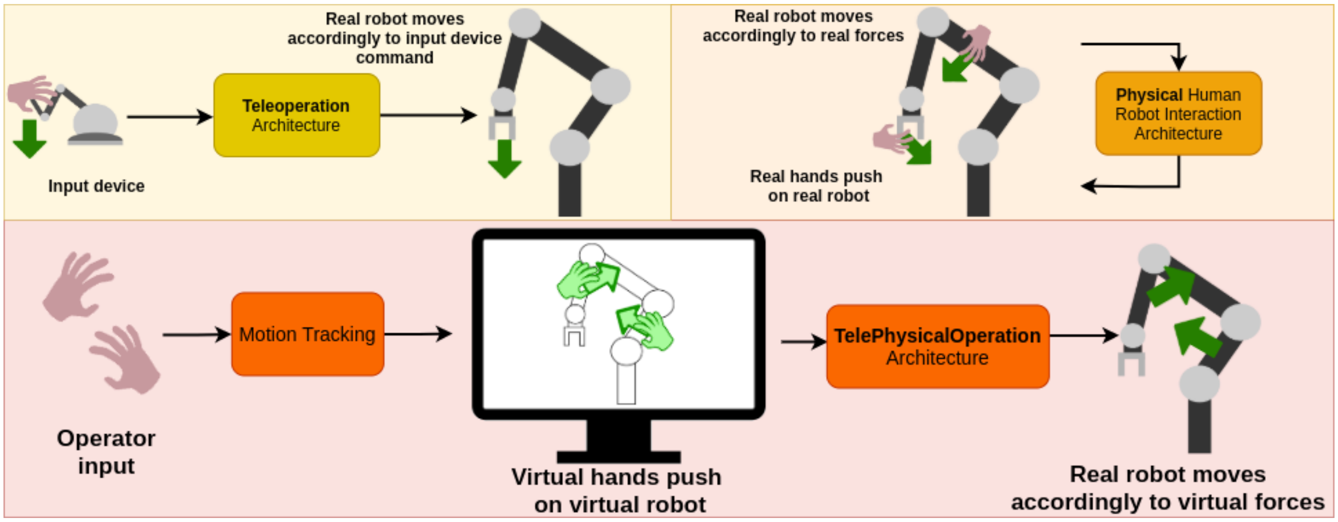


Fig. 1. Concept of TelePhysicalOperation. Above, schematics of the traditional teleoperation and the physical human robot interaction interfaces. Below, the scheme of TelePhysicalOperation, derived by the combination of the two above controlling interfaces.

robot Assistant (MOCA) is functioning autonomously, while the operator can choose to be physically coupled to the robot (through a mechanical admittance interface) to perform conjoined actions. MOCA robot is present again in [19], where an haptic guidance is performed to physically drive the arm to grasp the wanted object.

As stated in the above mentioned works, teleoperation interfaces may vary; however, especially for complex mobile robots, the control from a remote location remains a challenging task. At the same time, a very intuitive way to effectively guide and teach a robot how to execute a task is by physically interacting and driving it by applying forces on different parts of its body. However, such direct pHRI may not be possible for safety reasons in case of robotic systems with elevated power capabilities. By considering these observations and blending the teleoperation and the pHRI concepts, in this work we propose a novel approach, the *TelePhysicalOperation*, which enables the teleoperation of a remote mobile manipulation platform through a virtual physical interaction interface that enables the operator to generate and selectively apply virtual forces along the kinematic chain of the remote robot in a manner that resembles a user physically interacting with the robot through a virtual "Marionette" type of interface. The method permits to control complex and redundant robots providing increased flexibility in regulating the motions of the robot body beyond the end-effector level by allowing the operator to on-the-fly select the locations along the kinematic chain where these virtual forces are applied. It resembles an interface similar to the physical interaction paradigm of a user teaching and guiding a robot, thus it can also be employed for remotely interacting in an intuitive way with collaborative robots while avoiding at the same time any direct physical contact with the robots, ensuring safety.

TelePhysicalOperation is experimentally demonstrated and validated through a number of tasks executed with the CENTAURO robot [20], a hybrid leg-wheel system with an anthropomorphic upper body.

The rest of the paper is organized as follows. Section II introduces the concept of TelePhysicalOperation; Section III presents the motion capture interface used to provide the input requested by TelePhysicalOperation; Section IV describes the control architecture; Section V shows the experimental validations performed and Section VI draws the conclusions.

II. The Concept of TelePhysicalOperation

The overall concept of TelePhysicalOperation is schematically illustrated in Fig. 1. As it can be seen, TelePhysicalOperation emerges from the blending of teleoperation and physical interaction interfaces traditionally used to control and interact a remote or a collaborative robot respectively. The rationale idea of our approach is that such a combination can provide a universal and intuitive human robot interaction interface that can be suitable for interacting with either a remote robot (teleoperation) or a collaborative robot (collaboration) in a manner inspired by the way that a user today physically interacts with a collaborative robot during e.g. a teaching or guiding phase of the collaborative task. This is inspired by the fact that, when the operator physically interacts with the robot using multiple contact points, he/she has the possibility to precisely shape the pose of robot end-effector as well as regulate other motions permitted by the available robot redundancy to assist and accomplish the task. TelePhysicalOperation implements exactly such a multiple-contact interaction interface principle in a virtual manner permitting an operator to command a remote or a collaborative robot without the need of any physical interaction.

To realize this and to regulate the motions of the remote or collaborative robot, the TelePhysicalOperation concept relies on the application of virtual forces that can be selectively applied by the operator to different locations along the kinematic chain of the robot. Therefore, only *virtual* contacts are established between the operator and the real robot. As in pHRI, the remote/collaborative robot responds to these forces as if they were actual interaction forces, regulating accordingly its motions and resembling the motion response that the operator should expect when physically interacting

Fig. 2. The TelePhysicalOperation concept follows a “Marionette” type interaction: the operator generates virtual forces that can be selectively applied on specific locations on the robot segments.

and applying forces to the robot in real. The virtual forces are generated by virtual springs initiated at the arms of the human operator and terminated to the selected applied locations in the robot body approximating the “Marionette” motion generation principle, as illustrated in Fig. 2. The virtual forces requested as inputs by the framework are 3D vectors and their amplitude is controlled through the elongation of the virtual springs that is performed through suitable motions of the operator arms monitored by appropriate tracking devices. The main contributions of the proposed approach are summarized below:

- Differently from a standard end-effector based teleoperation, TelePhysicalOperation provides functionality that permits to control selectively different body segments of the robot allowing to regulate both the end-effector motions as well as the motion of the redundant degrees of freedom effectively.
- By relying on the proposed virtual forces, following the “Marionette” motion control principle, our method is transparent with respect to the particular robot kinematics and the associated redundancy. In other words the method does not have the burden of a particular master device to be mapped 1-to-1 to the remote robot to control, but it only requires an input device system that can track the motions of the operator, needed to generate the virtual forces that will be applied to the selected robot body locations.
- The TelePhysicalOperation concept permits to negotiate the potential safety constraint of the pHRI but keeping the intuitiveness of a physical contact with the robot body. This can be particularly applicable in the case of interacting with a high power and strength collaborative robot that may not permit to physically interact with due to safety regulations.

To realize the TelePhysicalOperation concept, we have developed an architecture based on two main components as depicted in Fig. 3:

- The *TelePhysicalOperation Suit* (TPO Suit), an effective low cost motion tracking interface for the operator, in charge of monitoring the movements of the operator arms and of providing the requested inputs for the TelePhysicalOperation interface and control architecture (Section III).
- The main control node, implemented on a pilot pc, which is responsible for handling the virtual forces based on the motion inputs received by the TPO suit and deriving the corresponding motions that should be generated by the robot due to the application of the virtual forces. This node implements the control modes used to facilitate the control of the remote robot through the inputs received by the operator (Section IV).

The TelePhysicalOperation architecture provides on the fly flexibility to quickly change the points where the virtual forces are applied. In addition it delivers additional features to assist the operator executing the remote task, i.e., the *Blocking Link* (Section IV-C) and the *Mirroring Motion* (Section IV-D) features. The implementation is based on the Robotic Operating System (ROS), a middleware well-known in the robotics community.

III. The TelePhysicalOperation Suit

The virtual forces to be applied to the remote robot body are generated through the motion inputs of the operator arms. To track the operator arms we have realized a lightweight and low cost motion capture solution, based on *Visual-Simultaneous and Localization Mapping* (V-SLAM) tracking cameras.

The *TPO Suit* is composed of:

- Two *Intel® RealSense Tracking Camera T265* worn on operator’s left and right arm’s wrists.
- A *Raspberry Pi 4 Model B* fully functional computer with highly compact dimensions allowing to mount it as a wearable device on the body of the operator.
- A compact battery bank, which provides power to the TPO Suit components.

The task of the worn computer is to synchronize the data coming from the different cameras, and to forward the computed virtual forces through the network to the pilot pc where the main control node of the TelePhysicalOperation is implemented. The cameras are connected to the Raspberry Pi through USB ports, while the Raspberry Pi communication with the pilot pc is handled with a Wi-Fi connection eliminating the need of any tethering between the operator who wears the TPO Suit and the pilot pc.

The T265 camera is a V-SLAM tracking device composed of two fisheye lens, an IMU, and a Visual Processing Unit (VPU). The V-SLAM algorithms run directly on the device, allowing for low latency and efficient power consumption. Its small size (108 x 25 x 13 mm) and its light weight ($55g$) make it very comfortable to be worn. By mounting the two cameras on the operator’s wrists, we can track the motion of the arms in any direction in the 3D space. Hence, at any instant we can choose to use the motions of two wrists to generate a pair of virtual forces that can be then selectively applied to two different locations of the robot body.

The computer of the TPO Suit receives the cameras data at a specific frequency of 100 Hz. For each camera, we gather its actual pose as a 4-by-4 transformation matrix $\boldsymbol{T}$. This matrix describes the 3D pose from the camera origin frame (the point where the camera has been switched on) to the actual camera frame. The operator can selectively set a reference frame at a particular pose of his/her arm during initialization, which results in $\boldsymbol{T}_{ref}$, a transformation from the origin frame to

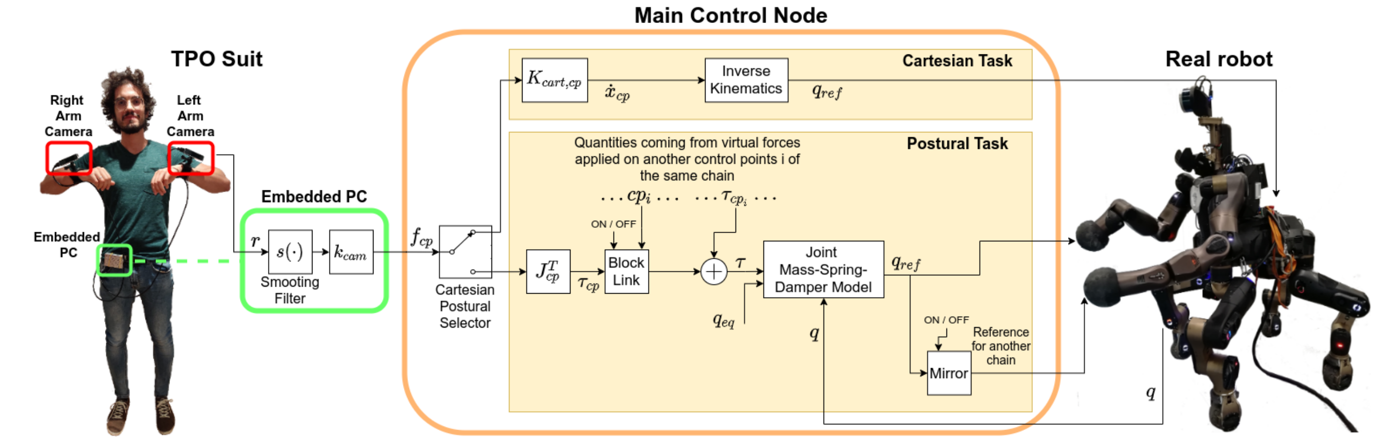


Fig. 3. The architectural scheme of TelePhysicalOperation. On the left, the operator is wearing the TPO Suit, which provides a virtual force $\boldsymbol{f}_{cp}$ to the main control node. The main control node is in charge of processing the virtual force based on the task associated with the control point chosen. On the right, the final references are sent to the robot.

the reference frame. Hence, the transformation $\hat{\boldsymbol{T}}$ from the reference frame to the actual frame is computed as:

$$\hat{\boldsymbol{T}} = \boldsymbol{T}_{ref}^{-1}\ \boldsymbol{T} \tag{1}$$

From $\hat{\boldsymbol{T}}$ we extract the translation component $\boldsymbol{r} \in \mathbb{R}^{3\times1}$, and we associate it with the elongation of a virtual spring to compute the final virtual force $\boldsymbol{f}_{cp} \in \mathbb{R}^{3\times1}$ (Fig. 3) as:

$$\boldsymbol{f}_{cp} = k_{cam}\ s(\boldsymbol{r}) \tag{2}$$

where $s(\cdot)$ is a simple filter to smooth out the behaviour, and k_{cam} is a positive gain representing the stiffness of the virtual spring. The vector $\boldsymbol{f}_{cp}$ describes the virtual force applied on the selected robot part, i.e., the control point cp located on a robot link. ROS services are provided to change on the fly the control points and to link them to the virtual forces generated by the motions tracked by the cameras of the TPO Suit. The virtual forces generated from each camera are then aggregated and sent to the main control node through ROS topics.

IV. TelePhysicalOperation Main Control Node

The main control node handles the incoming virtual forces $\boldsymbol{f}_{cp}$ and use them to generate the references for the joints of the robot. Depending on the chosen control point, each virtual force can be processed and explored in two ways:

- With the *postural motion generation* (Section IV-A), the virtual force is used to derive the joints position references for a *postural* task, i.e. a task at a joint-level. One or more virtual forces can be applied to different links of a single kinematic chain, resulting in the joints moving accordingly to the external virtual forces.
- With the *Cartesian motion generation* (Section IV-B), the virtual force is used to generate a motion of a *Cartesian* task on the control point by exploring the virtual force to generate a 3D Cartesian velocity reference for that point.

To help the operator in accomplish the tasks we have included two additional features: the *Blocking Link* feature, and the *Mirroring Motion* feature (Sections IV-C and IV-D).

The main control node runs on a pilot pc which handles the data received, shows through GUIs information on the current state of the systems, and sends the final commands to the robot with the *CartesI/O* Control Framework [21] and the XBot Architecture [22]. Visualization tools include the robot's representation on the ROS-standard kinematic visualizator RViz with visual feedback on the virtual forces applied.

A. Postural motion generation

To derive the references of the postural motion task, the virtual force $\boldsymbol{f}_{cp}$ is considered as a force acting on a control point cp, which can be selected at a location along the kinematic chain of joints N of the robot. From $\boldsymbol{f}_{cp}$, the resulting torques on the chain's joints $\boldsymbol{\tau}_{cp} \in \mathbb{R}^{N\times1}$ are computed:

$$\boldsymbol{\tau}_{cp} = \boldsymbol{J}_{cp}^{T}\ \boldsymbol{f}_{cp} \tag{3}$$

where $\boldsymbol{J}_{cp} \in \mathbb{R}^{3\times N}$ is the linear Jacobian matrix of the control point chosen, i.e., a matrix such that its product with the derivative of the configuration vector gives the 3D linear velocity of cp. Note that, if the control point is not on the last link of the robot chain, the virtual force will not influence the joints *after* the chosen link hence the Jacobian will have the final columns filled with zeros. In case that more than one virtual force is acting on different control points on the same kinematic chain, their contributions will be summed to a total joint torque $\boldsymbol{\tau}$ as follows:

$$\boldsymbol{\tau} = \sum_{cp \in chain} \boldsymbol{\tau}_{cp} \tag{4}$$

If the virtual forces are acting on different kinematic chains (e.g. on two different arms) each $\boldsymbol{\tau}$ is handled separately. For each controlled kinematic chain, having derived the corresponding total joint torque due to the application of the virtual forces, the joint reference motion is computed by considering a joint mass-spring-damper model (Fig. 3) as follows:

$$\begin{aligned} \ddot{\boldsymbol{q}}_{ref}(t) &= \boldsymbol{M}^{-1}\big(\boldsymbol{K}(\boldsymbol{q}_{eq} - \boldsymbol{q}(t)) - \boldsymbol{D}\dot{\boldsymbol{q}}_{ref}(t-1) + \boldsymbol{\tau}\big) \\ \dot{\boldsymbol{q}}_{ref}(t) &= \dot{\boldsymbol{q}}_{ref}(t-1) + \ddot{\boldsymbol{q}}_{ref}(t)\ \Delta t \\ \boldsymbol{q}_{ref}(t) &= \boldsymbol{q}_{ref}(t-1) + \dot{\boldsymbol{q}}_{ref}(t)\ \Delta t \end{aligned} \tag{5}$$

where $\boldsymbol{q}_{ref}(t) \in \mathbb{R}^{N\times1}$ is the joints position reference vector; $\boldsymbol{M}, \boldsymbol{K}, \boldsymbol{D} \in \mathbb{R}^{N\times N}$ are diagonal matrices of the mass, stiffness and damping parameters of the joint mass-spring-damper model; $\boldsymbol{q}, \boldsymbol{q}_{eq} \in \mathbb{R}^{N \times 1}$ are the current position of the joints and the equilibrium set point where a stiffness greater than zero will drag the joints; Δt is the time interval between two consecutive control loops. The parameters of the mass-spring-damper model can be set experimentally to regulate the motion behavior of the individual joints subject to the applied virtual torques derived by Eq. 4. As an example, the diagonal elements of the stiffness $\boldsymbol{K}$ can be set to zero to eliminate the returning elastic torque towards the equilibrium set point of the joints. Instead, by increasing these values, the joints will tend to go back to their $\boldsymbol{q}_{eq}$ set point if no virtual forces are applied to the control points on the robot chain.

B. Cartesian motion generation

Postural based motion control provides full flexibility to the operator to control the individual joints of the robot based on the control points selected on the robot body. This kind of motion control lets the user to regulate as needed the end-effector pose as well as the available redundancy if it exists. In some situation though, the possibility to regulate the motions of the remote robot at the task space may be required and it may be more appropriate to facilitate the execution of some tasks. For example, the operator can apply a virtual force on the control point set in the base of a mobile robot equipped with steering wheels, with the intention to move the whole mobile base. Another challenging Cartesian task can be to control the pose of a quadruped body by selecting a control point on the pelvis and driving its pose using the virtual force. Such a task would be challenging to be carried out through postural motion generation as it involves motions from several legs joints that contributes to the pose of the pelvis, e.g. making the platform going up or down ("squatting").

To realize the functionality of regulating specific links of the robot body in the corresponding task space, the proposed TelePhysicalOperation method provides a Cartesian motion generation interface, which, from the applied virtual force $\boldsymbol{f}_{cp}$, derives a velocity reference $\dot{\boldsymbol{x}}_{cp} \in \mathbb{R}^{3 \times 1}$ (Fig. 3) as follows:

$$\dot{\boldsymbol{x}}_{cp} = \boldsymbol{K}_{cart,cp} \; \boldsymbol{f}_{cp} \tag{6}$$

where $\boldsymbol{K}_{cart,cp} \in \mathbb{R}^{3 \times 3}$ is a diagonal matrix of gains based on the Cartesian task specific for the control point cp. From the resulting Cartesian velocity reference $\dot{\boldsymbol{x}}_{cp}$, a joint reference $\boldsymbol{q}_{ref}$ is derived with an inverse kinematic process.

This Cartesian motion generation interface permits also to limit the possible Cartesian directions to comply with the physical constraints of the robot or the specific requirements of the Cartesian task. This can be done by putting the correspondent elements in the diagonal of $\boldsymbol{K}_{cart,cp}$ equal to zero, for example to control the mobility of a planar mobile robot, which can not follow a velocity along the z axis.

C. The Blocking Link Feature

In the postural task, according to Eq. 3 and Eq. 4, each virtual force applied on a control point will contribute to command each joint from the chain's root up to the last joint before the control point. There are situations in which the operator may want to move only specific joints in the middle of the robot chain without influencing the position of the first joints of the chain. For example on the CENTAURO robot, one may want to move precisely the wrist joint while keeping the shoulder and elbow joints fixed, as it can be seen in the second image of Fig. 7. In the image, the virtual force applied on the end-effector is influencing only the wrist joint, because of the presence of another virtual force on the robot forearm, which is the only virtual force that can influence the shoulder and elbow joints. We call this the *Blocking Link* feature.

D. The Mirroring Motion Feature

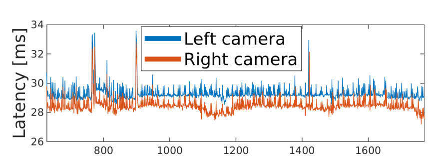
For a dual arm manipulation system, there are situations in which it is useful to command the two twin arms to move in a specular and symmetrical manner, like to execute a bi-manual object grasping action. Hence, we have implemented the *Mirroring Motion* feature, with which the virtual forces applied on a control point of an arm are also applied on the correspondent control point of the other arm, symmetrically (respect to an axis perpendicular to the floor).

A showcase of this feature is visible in the second image of Fig. 5, where the force applied on the right end-effector has been mirrored to the left end-effector. We have also taken advantage of this functionality to place a box on a platform, previously picked up with the two CENTAURO arms (last image of Fig. 9).

V. Experimental Validation

We have validated the TelePhysicalOperation method by performing a number of tasks with the CENTAURO platform, a quadruped body with wheels and a human-like torso with two arms. During these experiments the operator applies virtual forces to different robot body locations (i.e., the control points) to execute different tasks. The control points were selected by another person, the assistant pilot, through ROS services, according to the instruction provided by the first operator. The parameters of the joint mass-spring-damper model presented in the Eq. 5 have been experimentally tuned to adjust the sensitivity of the robot generated motions, while the virtual spring stiffness of the cameras k_{cam} has been experimentally set to $1.8 \, {}^{N}\!/_{m}$ based on the level of sensitivity in the motion produced that felt comfortable by the human operator.

We have performed some initial tests about the latency introduced by our framework, where the embedded pc connected with the cameras was communicating with the pilot pc through



	Mean [ms]	Std Dev [ms]
Left cam	29.30	0.47
Right cam	28.48	0.50

Fig. 4. Latency introduced by the TelePhysicalOperation framework. The time interval is calculated from the instant when the data is polled from each camera to the instant after the command references are sent to the robot (in Fig. 3, from the leftmost side of "Embedded PC" box to the rightmost side of "Main Control Node" box).

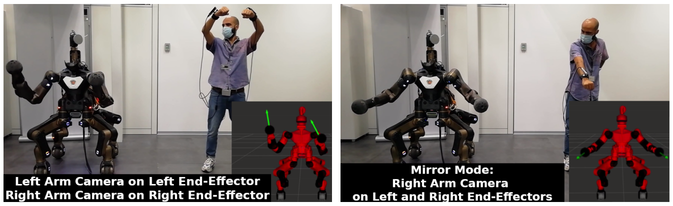


Fig. 5. CENTAURO's arms are moved by means of the TelePhysicalOperation interface. In the first image, each operator's arm is applying a virtual force on the respective robot end-effector. In the second image, the *Mirroring Motion* feature is used: with one arm the operator is applying two specular virtual forces on both robot end-effectors.

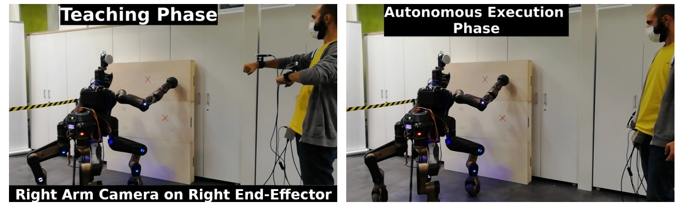


Fig. 6. TelePhysicalOperation interface is exploited for a remote collaboration. In the first image, the operator remotely guides the robot to specific workspace locations. In the second image, the robot executes autonomously a trajectory which follows the recorded locations.

Wi-Fi (Fig. 4). The latency between the instant in which the camera are polled to the instant in which the robot's commands are sent has resulted to be, on average, less than $30ms$. The difference between the two cameras was due to the fact that we poll one after the other.

The first experiment demonstrates a showcase in which the arms of CENTAURO are commanded within their workspace (Fig. 5). It can be observed that the TelePhysicalOperation interface results to not matching postures between the robot and the human operator. This is an expected behavior that is intrinsic to the employed "Marionette" based control. Indeed, this approach explores the virtual forces generated by the motions of the operator rather than the postural operator state to control the reference of the arm joints.

In the second experiment a remote collaboration between the operator and the robot is performed (Fig. 6). In this demonstration the operator, thanks to the TelePhysicalOperation interaction interface, moves the remote robot's end-effector to a number of workspace locations, which Cartesian positions are recorded. In a second phase the robot is commanded such that it performs autonomously a trajectory which follows the recorded positions. This demonstration in principle resembles the teaching phase of a human-robot collaboration but without the need to physically interact with the robot body to guide its end-effector. Indeed, the operator, using the proposed interface, can perform the teaching/demonstration phase from remote in a similar way as when the robot is guided through direct physical interaction.

In the third experiment we show how, by applying two virtual forces on the same arm, the operator can shape its pose and make the end-effector reach a goal location while avoiding an obstacle (Fig. 7). The task is to press a button obstructed by some bricks. The operator first activates the shoulder and the elbow joints to go over the obstacle, and then bend the wrist to reach the button from above. The plots in Fig. 8 show the relevant data gathered during the experiment. In the first and third plots, the camera inputs are depicted, i.e. the virtual forces $\boldsymbol{f}_{cp}$ of Eq. 2. For each input, the second and fourth plots show the joint torques generated with Eq. 3 and with the *Blocking Link* feature. Indeed, this feature nullifies the contribution of the right camera in the torque of some joints because another virtual force is applied with the left camera in an ancestor link. This permits to precisely control with the right camera only the *Elbj*, *ForearmPlate*, *Wrj1*, and *Wrj2* joints in the time interval from $t = 0s$ to $t = 16s$, and only the *Wrj1* and *Wrj2* joints in the time interval after $t = 20s$. The last three plots show the state of the robot's right arm during the experiment; please note that the Cartesian velocities (in the two bottom plots) have been computed from the derivation of the sensed robot joints position, hence they have been post-processed with a moving average filter to improve the visualization.

In the last experiment, a complex environment is set up in our laboratory (Fig. 9). The CENTAURO robot must be guided first through a low passage, which imposes the necessity to command the robot to perform a "squatting" motion. Then a box must be picked up with the two arms from one location, and put down in another site. The final placement of the box is made thanks to the *Mirroring Motion* feature, in which the operator with a single arm applies two identical specular virtual forces on the two robot's end-effectors. This experiment effectively validates the flexibility in applying up to two virtual forces in different parts of the robot, according to the needs of the task and the selection made by the operator. Plots are shown in Fig. 10. Like in the previous Fig. 8, the first and third plots show the input from the cameras. Differently from the previous experiments, in this case the virtual forces are used to generate not only *postural* motions (Section IV-A) for the arms, but also *Cartesian* motions (Section IV-B) for the robot body-locomotion. The second and fourth plots show the joints position of the two arms.

All the described experiments have been recorded, resulting in the video attached with this paper, available also at `https://youtu.be/dkBmbTyO_GQ`.

VI. Conclusions

We have presented TelePhysicalOperation, a novel concept to improve the classical robot teleoperation by exploring virtual physical human robot interactions through the intuitiveness of an approach that resembles controlling the remote robot in a "Marionette" based manner. By applying virtual forces selectively on points of the robot body, the operator can effectively teleoperate the remote robot. Different number of inputs can be applied on different robot parts, hence providing more possibilities than a classical Cartesian controller interface that focuses mainly on the end-effector control. A control architecture has been developed to realize the proposed concept, and an inexpensive motion tracking suit, the TPO suit, composed by tracking cameras, has been exploited to provide the necessary inputs. The whole framework has been evaluated on the CENTAURO robot demonstrating good efficacy and

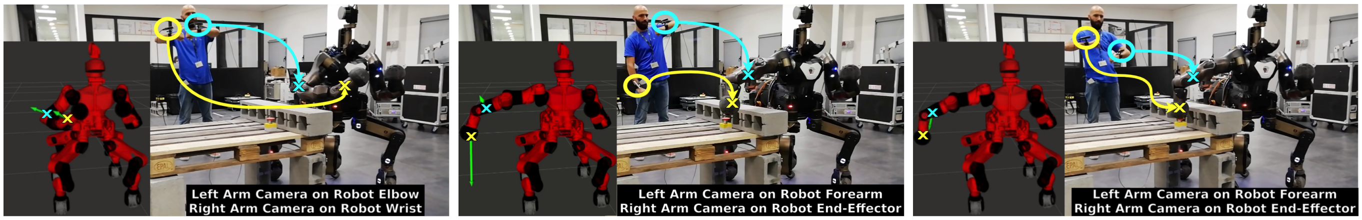


Fig. 7. In the button experiment, the goal is to command the robot arm to press a button obstructed by some bricks. The cyan and yellow marks indicate the control points where the virtual forces are applied by the two operator’s arms. Thanks to the TelePhysicalOperation interface, the operator can shape the robot arm to avoid the obstacle and reach the goal.

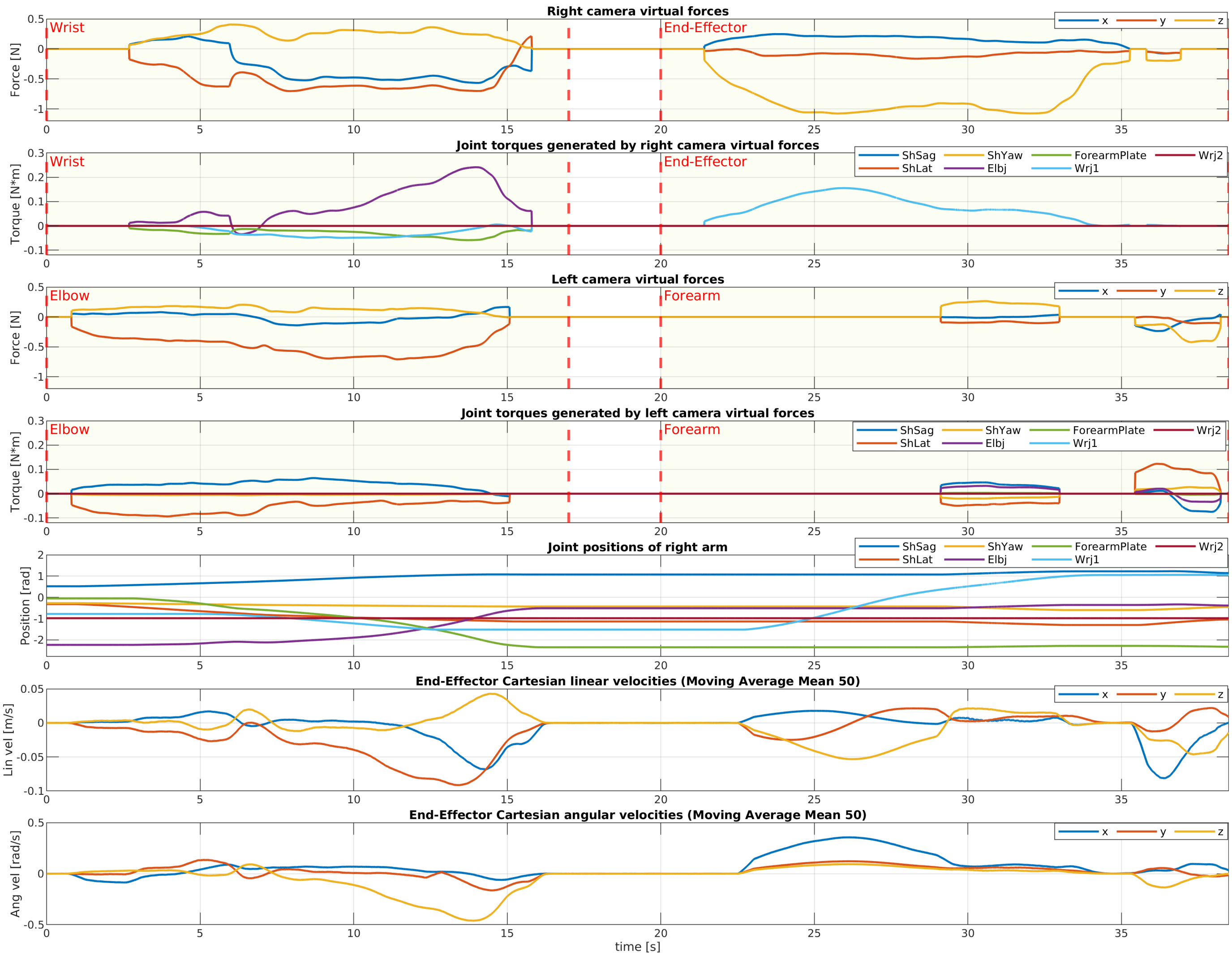


Fig. 8. Plots for the button experiment. For each virtual force $\boldsymbol{f}_{cp}$ generated by the right and left cameras (first and third plots, Eq. 2), joint torques $\boldsymbol{\tau}_{cp}$ are computed (second and fourth plots, Eq. 3). The control points where the virtual forces are applied are indicated by the areas delimited by the vertical red dashed lines (i.e. *Wrist*, *Elbow*, *End-Effector*, and *Forearm*). The joints positions of the robot’s arm varying during the experiment are visible in the fifth plot. In the two plots at the bottom, the End-Effector Cartesian velocities (filtered to improve the visualization) are shown.

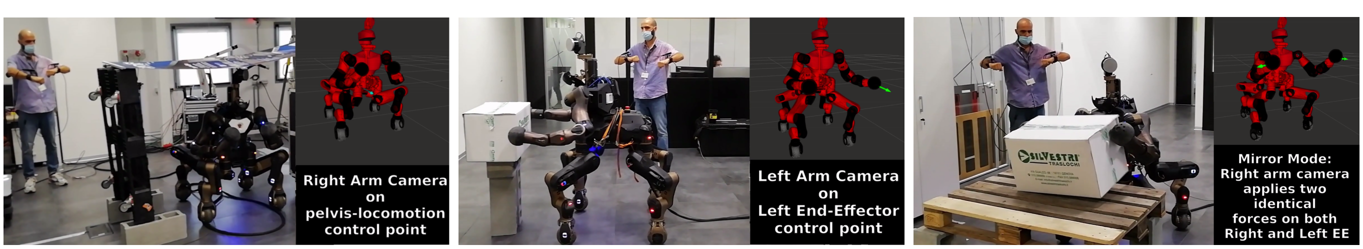


Fig. 9. The three phases of the locomotion and pick & place box experiment: in the first image, CENTAURO robot is passing below the low passage; in the second, the left arm is being positioned on the box side; in the third the box is being placed with the *Mirroring Motion* feature activated.

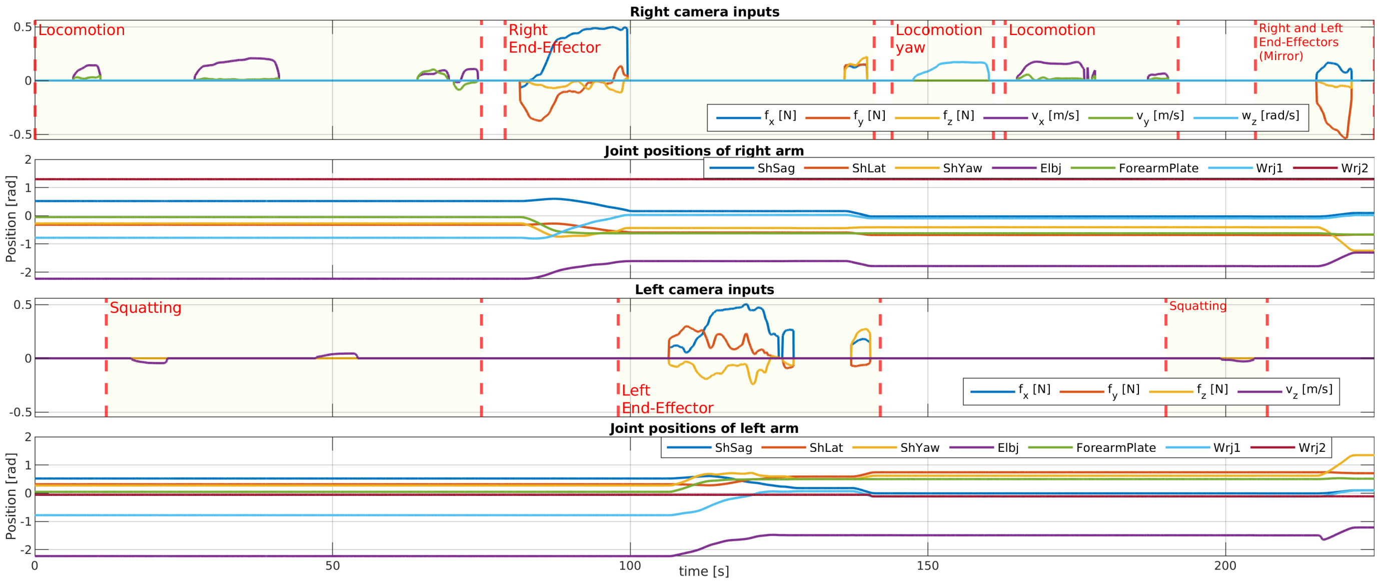


Fig. 10. Plots for the locomotion and pick & place box experiment. In the first and second plots, the camera inputs are shown. The different phases in which different control points are chosen are highlighted by the areas delimited by the vertical dashed red lines. For *Left* and *Right End-Effector* control points, the inputs generate postural motions (Eq. 3). For *Locomotion*, *Locomotion yaw*, and *Squatting* control points, the inputs generate Cartesian motions (Eq. 6). The joints position of the right and left arm varying during the experiment are visible in the second and fourth plots, respectively.

ability of the operator to command the execution of a number of tasks. Future works will concentrate on the development of additional features that will increase the intuitiveness of the proposed approach. The interface of the primary pilot will be extended with a handheld interface that will permit the primary pilot to autonomously switch to different control points without the need to request to the assistant pilot to perform this operation. Other future features will include the incorporation of a gesture recognition module that can assist to operator to initiate the execution of predefined motions, e.g. primitive manipulation actions.

Acknowledgment

The authors want to thank Dr. Alessio De Luca for the recording of the final experiments.

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