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# TelePhysicalOperation: a Shared Control Architecture for Intuitive and Smart Teleoperation of Complex Mobile Manipulators

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***Abstract*—Recent years have shown a growing demand toward automation in the industry and other contexts. To follow this trend, the research has to face some challenges to exploit the capabilities of complex robotic systems. Heavy redundant platforms, like dual arm manipulators, mobile robots, and legged systems, can help in accomplishing always more difficult tasks, but they also need more effort to operate with them. In this scenario, we have faced the challenge of exploring new teleoperation interfaces. With the development of the *TelePhysicalOperation* architecture, we want to provide: (1) an intuitive interface to permit even to a non expert user to control complex robots; and (2) more robot autonomy capabilities, to reduce the operator burden and to improve the performance of the teleoperation task.**

**This paper recaps our recent work done in this context, including experimental validations with the CENTAURO robot, a dual arm platform equipped with a hybrid leg-wheel mobile system.**

***Index Terms*—Telerobotics and Teleoperation; Physical Human-Robot Interaction; Dual Arm Manipulation; Mobile Manipulation; Industrial Robots**

## I. Introduction

Recent years have shown great advancements in the exploitation of robotic systems and intelligent machines in real applications [1]–[3]. Nevertheless, a lot of challenges remain to face to really take advantage of the additional capabilities of complex mobile/legged manipulator systems. Two major objectives are addressed by the work presented in this paper, as schematized in Fig. 1. The first objective is the development of more intuitive interfaces, that can help the operator to command the robot without the necessity of a specific training. The second is the improvement of the robot intelligence, by the addition of autonomy modules, to relieve the operator from considering all the aspect of a task that can be instead faced autonomously by the robot.

In the past, many works have addressed these challenges. A lot of intuitive interfaces that track the operator body to directly teleoperate the robot have been explored. By tracking multiple parts of the human body, multiple inputs can be provided to control all the degrees of freedom of a complex robot. Some solutions include the use of full body Inertial Measurement Unit (IMU) suits [4], Electromyography (EMG) interfaces [5], [6], tracking cameras mounted on the human body [7], and human skeleton tracking from camera images [8]. In parallel, the challenge of controlling complex robotic systems has been addressed by intelligent human-robot teleoperation interfaces, by adding some autonomy modules in a shared control or shared autonomy fashion [9]. For example, the interface can help the operator to switch between manipulator and mobile base control when necessary [10], [11], to grasp an object [12], or to maintain the grasp while handling the object [13]–[15].

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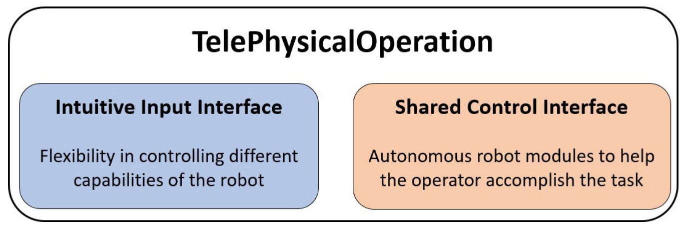


Fig. 1. Schematic of the two major objectives addressed by the TelePhysicalOperation architecture.

In this regard, we have presented the concept of TelePhysicalOperation [7], a blending between the classical teleoperation and a physical human-robot collaboration, which permits to control the robot at a safe distance but maintaining the intuitiveness of the physical human-robot interaction. In other works [11], [15], we have expanded the architecture by introducing more robot autonomy modules to increase the performance of the task.

## II. TelePhysicalOperation

When operating a robot for guiding/teaching tasks, the operator has the possibility to precisely shape the pose of the robot by intuitively interacting with its body parts. The Tele-

PhysicalOperation architecture implements such a multiple-contact interface principle, but in a virtual manner, permitting a safe operation at a distance without the need of a physical interaction. To realize such a principle, the architecture relies on the application of virtual forces along the kinematic chain of the robot. The robot responds to these forces regulating its motion to comply with them, as in a physical human-robot interaction. These virtual forces are generated by virtual springs which link the arms of the human operator and the selected robot body parts, resembling a "Marionette" motion generation interface (Fig. 2). In-depth details of this interface are presented in [7].

The architecture is flexible enough to be applied to different types of robots, from fixed manipulators to complex mobile systems, such as the CENTAURO platform [16] shown in Fig. 2. Indeed, the virtual forces can be applied not only to the links of the arm kinematic chain, but also on the body of the mobile robot to exploit its mobility features. A change of the control point is necessary each time the operator wants to virtually push/pull the mobile base instead of the arm, an operation that is repetitive and may increase the operator effort and the task execution time. To address this problem, we have proposed a shared control interface for locomanipulation tasks to automatically generate mobile base motions even when only the arm is commanded [11]. In such a way, the operator can control exclusively the arm, without taking care of changing the control modality from the arm to the mobile base, and without taking care of the arm limited workspace. The proposed interface considers the manipulability level of the arm [17], a measure strictly related to the kinematic singularities of the limb. If the robotic arm reaches a workspace region in which the manipulability in the direction of the applied virtual force is low, the generated motion is gradually switched to the mobile base. This permits to reach the desired end-effector goal assuring that the manipulability does not decrease beyond a defined threshold. Furthermore, without the necessity of switching from arm control to mobile base control, the effort of the operator, as well as the execution time of the task, are reduced.

In the context of dual arm manipulation, some level of robot autonomy is often necessary to accomplish successfully the task. In [11], [15], we have addressed the problem of bimanual object picking and transporting. While the robot is carrying a load, it is often difficult for the operator to understand the forces applied to the object. This may result in applying an insufficient amount of forces, making the object fall, or an excessive amount, with the risk of "squeezing" too much the object and damaging it. The proposed interface enables the robot to autonomously reach and grasp the object with the two arms and to maintain a stable grasp while the operator commands only the object velocities. The unknown mass of the object is estimated by the system from the estimated forces sensed at the end-effectors. This allows to regulate the grasping forces according to the estimated mass to permit a safe transportation while the operator commands object velocities. Thanks to the shared locomanipulation feature, from

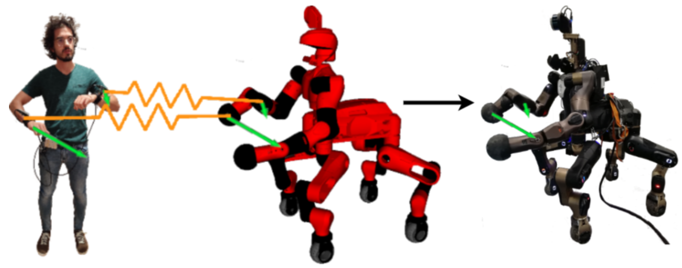

Fig. 2. The TelePhysicalOperation concept resembles a "Marionette" interface: through virtual springs, the operator applies virtual forces on the selected robot body parts, and the robot will generate compliant motions.

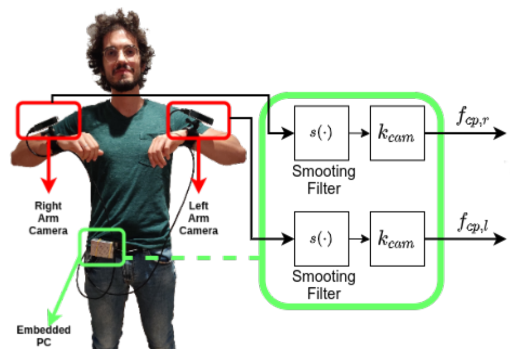


Fig. 3. The *TPO suit*, the motion tracking interface used to gather operator arm movements and generate virtual forces $\boldsymbol{f}_{cp}$

the commanded object velocities both arms and mobile base motions are generated. Therefore, during the object transport task, the operator does not have to worry about maintaining the grasp or generating the arm or mobile base motions as necessary.

## III. TelePhysicalOperation Suit

The TelePhysicalOperation architecture relies on a simple motion tracking interface to track the movements of the operator arms that are used to generate the virtual forces. We have adopted a low-cost solution, the *TPO Suit* (Fig. 3), based on Visual-Simultaneous and Localization Mapping (V-SLAM) tracking cameras. With these cameras, mounted on the two operator wrists, it is possible to track the movement of the operator arms. The displacement of each camera with respect to a reference position, after being filtered to smooth the behavior, is then associated with the elongation of the virtual spring (of stiffness $k_{cam}$) used to compute the final virtual force $\boldsymbol{f}_{cp}$ that will be applied to the selected robot body part. The cameras can be connected to a lightweight embedded PC, which can communicate with the external nodes via Wi-Fi connection, eliminating the need for any tethering between the operator and the robot.

## IV. Applications

The intuitiveness of the TelePhysicalOperation interface and its shared control modules have been experimentally validated in various experiments carried out with the CENTAURO [16], a hybrid leg-wheel platform with an anthropomorphic upper

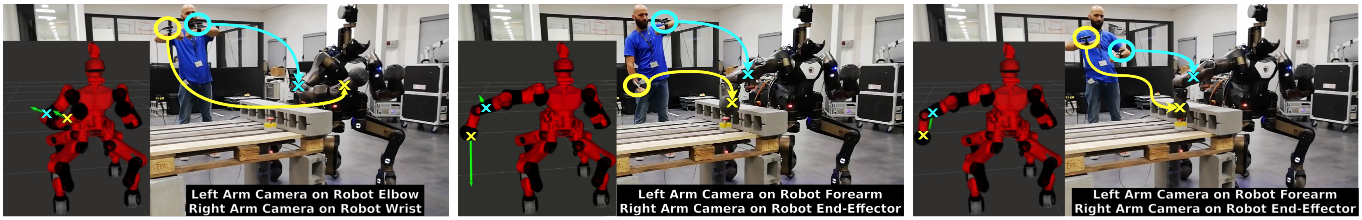


Fig. 4. In this experiment the goal is to teleoperate the robot right arm to press a button obstructed by some bricks. The cyan and yellow marks indicate the control points where the virtual forces are applied by the two operator arms. The robot visualization shows the input directions commanded by the user (green arrows). Thanks to the TelePhysicalOperation interface, the operator can shape the robot arm to avoid the obstacle and reach the goal. The experiment is taken from [7].

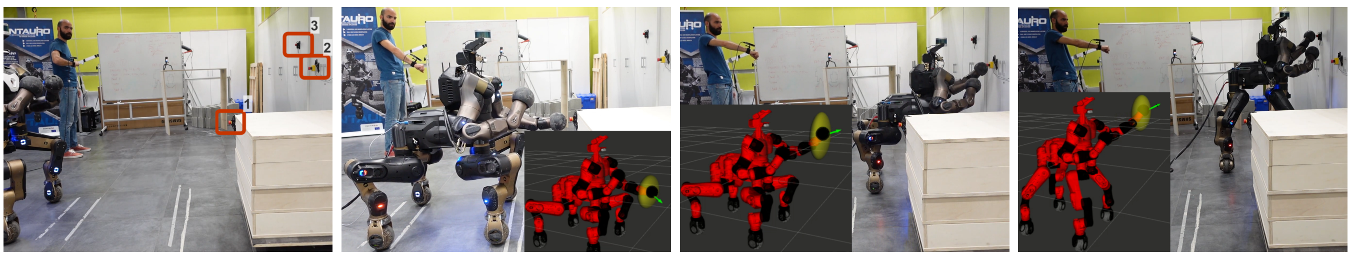


Fig. 5. In this experiment the left arm of the robot is teleoperated with the aim to press the three buttons highlighted in the leftmost image. The robot visualization shows the input directions commanded by the user (green arrows) and the manipulability ellipsoid of the robot left end-effector (yellow shape). The operator commands only the end-effector control point: thanks to the manipulability-aware shared locomotion, the motion is distributed between the arm and the mobile base. The experiment is taken from [11].

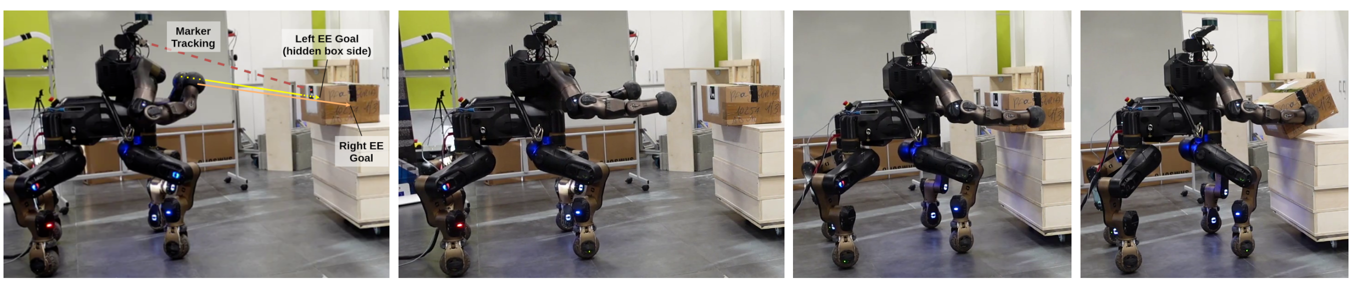


Fig. 6. In this experiment the robot autonomously reaches the box which is tracked thanks to a vision system based on *ArUco* markers. The robot then grasps the box with the two arms, imposing a grasping force that will be kept during the teleoperation phase shown in Fig. 7

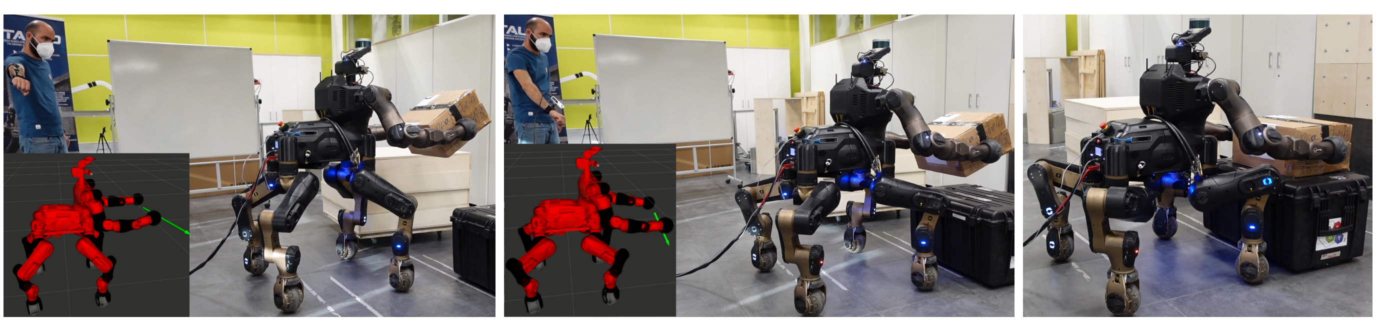

Fig. 7. After the box is collected, the robot is teleoperated to transport the load to another location. The manipulability-aware shared locomotion is combined with another feature which permits to autonomously regulate the grasping forces applied on the object while accepting the operator commanded object velocities (shown as the green arrows in the robot visualization). The experiment is taken from [11].

body. The implementation is based on the Robotic Operating System (ROS) [18] and two frameworks developed in our laboratory, XBot [19] and CartesI/O [20].

In an experiment from [7], we show the teleoperation of the CENTAURO robot with the aim to reach an end-effector goal (a button to be pressed) while avoiding some obstacles (bricks) (Fig. 4). With the application of two virtual forces on two different points of the same arm of the robot, the operator is able to first activate the shoulder and the elbow joints to go over the obstacles (first image) and then bend the wrist to reach the goal from above (second and third images).

In an experiment from [11], we show the manipulability-aware shared locomanipulation exploited to reach three different end-effector locations by combining the motion generation of the arm and the mobile base (Fig. 5). The operator does not need to switch from different control modes (arm and base): when the arm is dragged in a direction where the manipulability is low, the arm stops and it is the robot body that moves in the wanted direction.

Another experiment from [11] regarded a bimanual object picking and transportation. In the first phase (Fig. 6) the robot is able to reach and grasp the box autonomously by a combination of arms and mobile base motions. The box location is tracked through a vision system based on *ArUco* markers. After the box is collected, the second phase begins (Fig. 7). The robot is teleoperated to transport the box to another location. The manipulability-aware shared locomanipulation feature is combined with an autonomy module that regulates the grasping forces applied on the object. The result is that the operator has to command only object velocities, without worrying about arms manipulability, about switching from arms control to locomotion control, and about the grasping forces necessary to transport the load without dropping or damaging it.

The described experiments have been included in the video attached to this paper, and they are also available online at the following links: `https://youtu.be/dkBmbTyO_GQ` and `https://youtu.be/7YqfVn8XvNk`.

## V. Conclusions and on-going works

We have presented TelePhysicalOperation, a teleoperation architecture for mobile manipulators, developed to further advance toward a broader application of complex robots in real environments. By exploring the "Marionette" principle, the robot can be intuitively teleoperated through the application of virtual forces, that resembles a physical human-robot interaction but with the safety of a remote teleoperation. Shared control techniques have been explored too, to provide the robot with the intelligence necessary to automatize some parts of the task, reducing the operator burden and increasing the task performance. On-going works aim to further improve the teleoperation interface to address more complex tasks. An handheld interface will permit the operator to sense some haptic feedback regarding the status of the robot and of the task, providing information that is not so easy to understand just by watching the robot. In the next future, more complex dual arm asymmetric tasks will be considered, as well as more local autonomy features to assist the operator.

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