Towards a Cooperative Framework for Interactive Manipulation Involving a Human and a Humanoid

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Abstract— **In this paper we propose a novel approach for interactive manipulation involving a human and a humanoid. The interaction is represented by means of the relative configuration between the human's and the robot's hands. Based on this principle and a set of mathematical tools also proposed in the paper, a large set of tasks can be represented intuitively. We also introduce the concept of *simultaneous handling using mirrored movements*, where the human controls the robot and simultaneously interacts with it by means of a common manipulated object. Illustrative experiments are performed to validate the proposed techniques.**

I. Introduction

Cooperation is related to the action of working and/or acting together towards a common goal. Two or more entities cooperate when there is substantial gain of executing the task in this manner, instead of doing it alone.

Interaction between humans and robots is particularly appealing, and its development may lead to novel and unforeseen applications, whereas new challenges need to be faced. In this area, extensive is the literature that explores social, cognitive, or behavioral aspects of human-robot interaction [1]. Here, however, we are mainly interested in physical interaction between humans and robots.

An interesting classification of possible cooperation tasks is based on the level of control assumed by the human or the robot. In one important class of applications, for instance, the human holds complete control of the task execution. The examples in this class range from teleoperated robots to devices controlled by different forms of force control, such as [2]. On the opposite extreme, there are less common applications where mainly the robot controls the pace with which the task is performed, such as [3]. Finally, there are also applications where shared control of the tasks exists, as often occurs in rehabilitation robotics [4].

All the aforementioned applications share the feature that the cooperative task must be properly defined in order to be provided to the system controller. However, although simple verbal task definition is often enough for human understanding, finding precise mathematical task descriptions for robot control may be a complex procedure. For that reason, some works found in the literature focus on the execution of specific cooperative tasks only, e.g., handing over [5], [6], crank-rotation [7] or carrying a large object in an indoor environment while avoiding obstacles [8].

Considering the problem of describing mathematically a large set of tasks, in this work we explore an original and intuitive approach for human-robot interaction. Our idea starts with the definition of the cooperative tasks using the relative poses between the human and the robot. Then, using different manipulation tasks between a human and a humanoid as an experimental platform, we investigate how simple task descriptions may produce significant and complex cooperation. For instance, we investigate the task of pouring water, the teleoperation with collaboration, and the task of simultaneous handling using mirrored movements.

Based on this original approach for interactive human-robot cooperation, an integrated framework that simplifies the implementation in real systems is also proposed in the paper. The framework is designed to ensure that different cooperation scenarios may be managed in the same manner. We use dual quaternions to represent both human and robot poses, as well as the cooperative task. In addition, a new geometrical operation in the dual quaternion space is introduced, potentially simplifying both task definition and the experimental setup.

The results presented in the paper refer to cooperative manipulation tasks involving a human and a humanoid. The tasks were chosen in order to illustrate the broad range of scenarios comprised in the proposed strategy. Nevertheless, using the simple task definitions described here may also prove itself helpful while using different human-robot cooperation strategies. In cooperative handling of heavy objects using force control, for instance, the proposed technique may be used to easily conduct the robot to the correct grasping spot. For those reasons, we believe such intuitive interaction scheme may be an important tool in the design of effective service robots to assist humans with limited motion, such as spinal cord injured patients [9], or other motor disorders [10].

II. Intuitive task definition

Within the classes of cooperative manipulation tasks mentioned in the previous section, most of the applications may be described by the relative pose between the human's and the robot's hand. For some tasks, this description does not fully defines the task, since, for instance, objects must be picked up before actual manipulation. However, even in this condition, the cooperative task itself may be described in terms of relative motion between the human's and the humanoid's arms. Moreover, relative poses may be much

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easier to describe than the evolution of both absolute poses in time. It is based on this intuition that we develop the strategy for interactive cooperation involving a human and a humanoid presented in this section.

In order to better illustrate the sort of cooperative task concerned in this work, let us consider the tasks shown in Fig. 1. In the case of pouring water, the task can be completely defined by its geometry, that is, by the geometric relationship between the hands, and thus position control suffices to accomplish the task, since no contact is involved. In the case of handing over an object, the phase where the hands are moving towards each other can also be defined geometrically, and also executed by a position controller. Turning a crank, on the other hand, normally is defined by means of the forces involved in the interaction, for small disturbances in the positioning can lead to large interaction forces. However, in the case of human/humanoid interaction, we can assume that the force control will be managed by the human hand. Then, the intuitive task strategy can be used and valid as well. Note that, in all represented cases, the relative pose between the human's and the robot's hands remains the same or presents uncomplicated changes. In this way, we may execute several different cooperative tasks with a reduced number of relative poses or primitives.

For most of the applications similar to the ones illustrated in Fig. 1, adapting in real time the performed motion (either the robot or the human) in reaction to the other's motion is fundamental for effective cooperation. Indeed, this online adaptation is what defines the concept of cooperative behavior. In this context, using our proposed strategy to change the initially predicted motion and still achieve effective cooperation is natural and intuitive, since the task is defined as the relative pose between the human and the robot.

In order to apply this idea in real problems, we now address some issues that need to be formalized. First, we establish in Section III the mathematical model that describes the cooperative task and also the control strategy that can be applied using this mathematical description. Next, in Section IV a technique to obtain the relative pose between the human's and the robot's hands in different experimental scenarios is presented.

III. Mathematical model for the cooperation task

In this section, the problem is to define a mathematical framework which enables us to describe the cooperative tasks in a straightforward fashion. Thus, we define the cooperative tasks by means of the relative poses between the robot and the human. Hence, based on the task and the human's current pose, the robot must adapt online its motion.

The human/robot cooperation in terms of arms' coordination can be described by using the cooperative dual task-space representation [11]. In this approach, both the robot and the human arms are considered as manipulators sharing the same workspace and their end-effector configurations are represented by the dual quaternions $\underline{\mathbf{q}}_R$ and $\underline{\mathbf{q}}_H$, respectively.

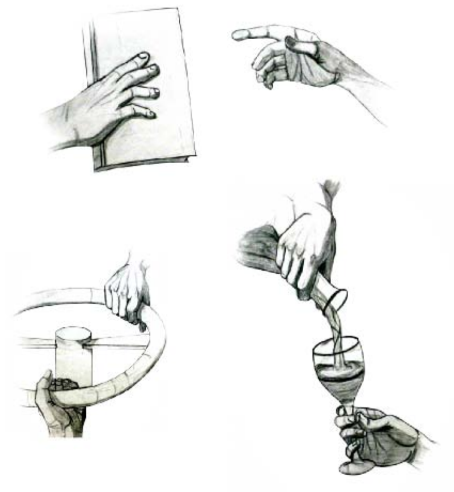


Fig. 1: Tasks are defined by the relative configuration between the hands.

The relative configuration between the arms is

$$\underline{\mathbf{q}}_{\text{task}} = \underline{\mathbf{q}}_R^* \underline{\mathbf{q}}_H, \tag{1}$$

where $\underline{\mathbf{q}}^*$ is the conjugate of the dual quaternion. As the task is defined in terms of $\underline{\mathbf{q}}_{\text{task}}$, it is convenient to decompose this variable in terms of the relative translation and the relative orientation, that is,

$$\underline{\mathbf{q}}_{\text{task}} = \mathbf{q}_{\text{task}} + \epsilon \frac{1}{2} \mathbf{t}_{\text{task}} \mathbf{q}_{\text{task}}, \tag{2}$$

in which $\mathbf{q}_{\text{task}}$ is the quaternion that represents the orientation between the arms and $\mathbf{t}_{\text{task}}$ is the pure quaternion (i.e., the quaternion with the real part equals zero) that represents the translation between them.

The robot control can be straightforwardly performed if the forward kinematic model (FKM) is given directly in the dual quaternion space [12], since

$$\dot{\underline{\mathbf{q}}}_R = \mathbf{J}_R \dot{\vec{\theta}}_R, \tag{3}$$

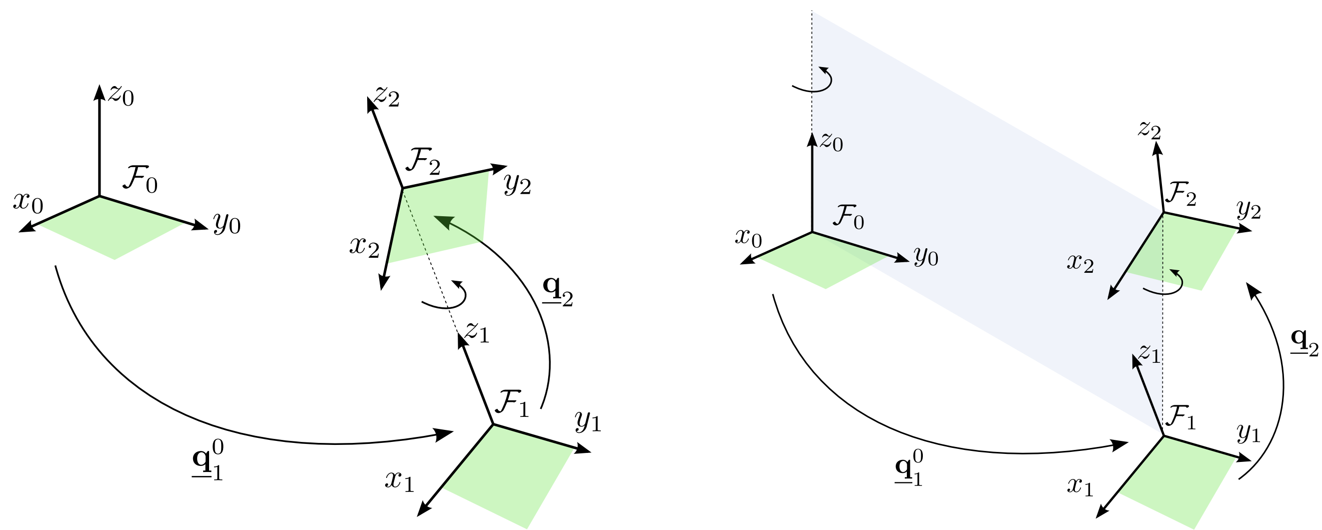
where $\vec{\theta}_R$ is the vector of joint variables of the robot arm and $\mathbf{J}_R$ is the analytical Jacobian. Then, the classic control law can be applied

$$\dot{\vec{\theta}}_R = \mathbf{J}_R^{\dagger} \mathbf{K} \left(\underbrace{\underline{\mathbf{q}}_{H_m} \underline{\mathbf{q}}_{\text{task}}^*}_{(1)} - \underline{\mathbf{q}}_{R_m} \right), \tag{4}$$

where $\mathbf{J}^{\dagger} = \mathbf{J}^T \left(\mathbf{J}\mathbf{J}^T + \lambda \mathbf{I} \right)^{-1}$ is the damped least-square inverse [13], $\mathbf{K}$ is a positive definite gain matrix and $\underline{\mathbf{q}}_{H_m}$ and $\underline{\mathbf{q}}_{R_m}$ are the current poses of the human's and robot's hands, respectively.

IV. Robot's perception of the human motion

Let us consider the setup illustrated in Fig. 4. The robot hand use $\mathcal{F}_T$ as its reference frame, but the pose of the human hand is given with respect to $\mathcal{F}_E$, the coordinate system of the motion tracker. Since we want to describe the collaboration using (1), both the human hand's and robot hand's poses should be expressed with respect to a



(a) (b)

Fig. 2: Difference between (a) the standard and (b) the decompositional dual quaternion multiplications.

common frame. However, the relationship between $\mathcal{F}_E$ and $\mathcal{F}_T$ depends on the robot's and tracker's physical placement. For practical reasons, we do not want to find the exact relationship between these two frames. Rather, our goal is to use a methodology that give a reasonable invariance with respect to the physical placement of the robot and the motion tracker. Hence, in Section IV-A we start by introducing a general mathematical operation that will provide an invariance with respect to the frame being modified and then in Section IV-B we apply this operation in our specific setup in order to obtain the desired invariance with respect to the physical placement between the robot and the motion tracker.

A. *Decompositional multiplication*

When representing a sequence of rigid motions by a sequence of dual quaternion multiplications—e.g., $\underline{\mathbf{q}}_i^0 = \underline{\mathbf{q}}_1^0\underline{\mathbf{q}}_2^1\dots\underline{\mathbf{q}}_i^{i-1}$—an intermediate transformation is always given with respect to the previous frame. For example, if the transformation $\underline{\mathbf{q}}_i^{i-1}$ consists in performing a translation along the x axis followed by a rotation around the z axis, actually we use $\mathcal{F}_{i-1}$ as the reference coordinate system for the transformation. However, in some situations it can be useful to perform the same transformation $\underline{\mathbf{q}}_i^{i-1}$ to the frame $\mathcal{F}_{i-1}$, but using another coordinate system as the reference. In the following we are going to define this new operation, called decompositional multiplication, along with an example illustrating the difference between the traditional operation and the proposed one.

Definition 1: Given the unit dual quaternion $\underline{\mathbf{q}} = \mathbf{q} + \epsilon\mathbf{q}'$, the operator $\overset{+}{\underline{\mathbf{t}}}\left\{\underline{\mathbf{q}}\right\}$, or simply $\overset{+}{\underline{\mathbf{t}}}$ for brevity if there is no ambiguity, is given by

$$\overset{+}{\underline{\mathbf{t}}} = \underline{\mathbf{q}}\mathbf{q}^* \tag{5}$$

More specifically, if the unit dual quaternion is given by $\underline{\mathbf{q}}=\mathbf{q}+\epsilon\frac{1}{2}\mathbf{t}\mathbf{q}$, then $\overset{+}{\underline{\mathbf{t}}} = 1 + \epsilon\frac{\mathbf{t}}{2}$ corresponds to the translation component of $\underline{\mathbf{q}}$.

Definition 2: The decompositional dual quaternion multiplication, represented by $\otimes$, is a binary operation that has precedence over the standard dual quaternion multiplication and is given by

$$\underline{\mathbf{q}}_1 \otimes \underline{\mathbf{q}}_2 = \overset{+}{\underline{\mathbf{t}}}_2\overset{+}{\underline{\mathbf{t}}}_1\mathbf{q}_2\mathbf{q}_1 \tag{6}$$

Let us see the difference of the standard and the decompositional multiplications by means of an example. Assume $\underline{\mathbf{q}}_1^0$ and $\underline{\mathbf{q}}_2$ unit dual quaternions, where $\underline{\mathbf{q}}_1^0$ is the homogeneous transformation from the frame $\mathcal{F}_0$ to the frame $\mathcal{F}_1$, and $\underline{\mathbf{q}}_2$ corresponds to a translation in z followed by a rotation around z, as illustrated in Fig. 2a. The standard multiplication

$$\underline{\mathbf{q}}_1^0\underline{\mathbf{q}}_2 = \mathbf{q}_1^0\mathbf{q}_2 + \epsilon\left(\mathbf{q}_1^0\mathbf{q}_2' + \mathbf{q}_1^{0\prime}\mathbf{q}_2\right)$$

performs an homogeneous transformation $\underline{\mathbf{q}}_2$ on $\underline{\mathbf{q}}_1^0$ with respect to $\underline{\mathbf{q}}_1^0$, meaning that both translation and rotation will be performed using z_1 of the frame $\mathcal{F}_1$ as reference. On the other hand, the decompositional multiplication

$$\underline{\mathbf{q}}_1^0 \otimes \underline{\mathbf{q}}_2 = \overset{+}{\underline{\mathbf{t}}}\left\{\underline{\mathbf{q}}_2\right\}\overset{+}{\underline{\mathbf{t}}}\left\{\underline{\mathbf{q}}_1^0\right\}\mathbf{q}_2\mathbf{q}_1^0$$

represents the same transformation $\underline{\mathbf{q}}_2$, that is, a translation in z followed by a rotation around z, but now using as reference the frame $\mathcal{F}_0$, as illustrated in Fig. 2b.

B. *Invariance with respect to physical placement between the robot and the motion tracker*

As we have seen in the previous sections, we measure the robot hand's and the human hand's poses with respect to different coordinate systems, i.e. $\underline{\mathbf{q}}_R^T$ and $\underline{\mathbf{q}}_H^E$, respectively. However, for practical reasons, we would like to avoid the requirement to specify the exact physical relationship

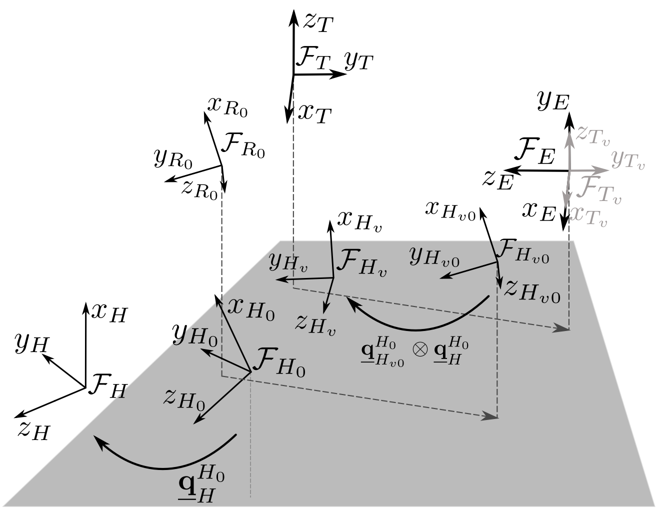


Fig. 3: Representation of the frames in the teleoperation task. In this illustration, we are assuming $\underline{\mathbf{q}}_{H_{v0}}^{T_v} = \underline{\mathbf{q}}_{R_{v0}}^{T_v}$. In the other cooperation tasks, $\underline{\mathbf{q}}_{H_{v0}}^{T_v} = \underline{\mathbf{q}}_{R_{v0}}^{T_v}\,\mathbf{q}\,(x,\pi)$, where $\mathbf{q}\,(x,\pi)$ means a rotation of π rad around the x axis.

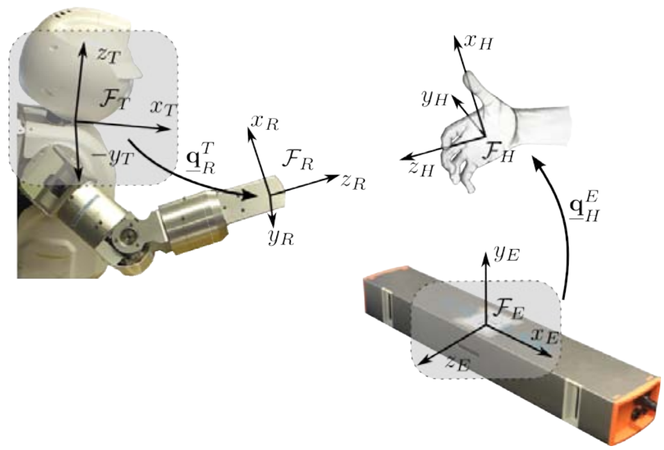


Fig. 4: Experimental setup. The subject's hand is expressed with respect to $\mathcal{F}_E$ whereas the robot's hand is expressed with respect to $\mathcal{F}_T$.

between the robot's and the motion tracker's coordinate systems. In order to develop our reasoning, first let us consider that we are performing a teleoperation, where the robot imitates the subject's movement—afterwards, we will straightforwardly extend this idea to the other cooperation tasks. In this task, the robot has to perform, with respect to its own torso, the same movement that the subject does with respect to his/her torso, and then $\underline{\mathbf{q}}_{\text{task}} = 1$, implying in $\underline{\mathbf{q}}_H = \underline{\mathbf{q}}_R$. Additionally, we consider that the initial poses of both the robot's and the human's hands, i.e. $\underline{\mathbf{q}}_{R_0}^T$ and $\underline{\mathbf{q}}_{H_0}^E$ [1], are the same pose with respect to their own torsos.

In order to address this problem of invariance, one of the first issues is that we can only measure the human's hand with respect to $\mathcal{F}_E$. Thus we define a virtual torso $\mathcal{F}_{T_v}$ with the same origin of $\mathcal{F}_E$, but aligned with $\mathcal{F}_T$, as illustrated in Fig. 3. Following, we also define the frame $\mathcal{F}_{H_{v0}}$ such that $\underline{\mathbf{q}}_{R_0}^T = \underline{\mathbf{q}}_{H_{v0}}^{T_v}$. Defining these two virtual frames is important in order to achieve invariance with respect to translational displacement between the robot, the motion tracker and the person.

For practical reasons, it is not easy to superpose $\mathcal{F}_{H_0}$ to $\mathcal{F}_{H_{v0}}$, meaning that $\underline{\mathbf{q}}_{H_v}^{T_v} \neq \underline{\mathbf{q}}_H^{T_v}$ and hence that $\underline{\mathbf{q}}_H^{T_v}$ may not simply be used as the reference to be passed to the robot. So, in order to enable that the movement performed by the subject with respect to its initial configuration $\mathcal{F}_{H_0}$ will be replicated by the robot, we may use $\mathcal{F}_{H_{v0}}$ as the reference. The decompositional multiplication turns out to be quite useful in this case, since we want to represent $\underline{\mathbf{q}}_{H_{v0}}^{H_0}$ considering the transformation $\underline{\mathbf{q}}_H^{H_0}$, i.e., we want to modify the frame $\mathcal{F}_{H_{v0}}$ by the transformation $\underline{\mathbf{q}}_H^{H_0}$, but using $\mathcal{F}_{H_0}$ as the reference frame. Thus,

$$\underline{\mathbf{q}}_{H_v}^{H_0} = \underline{\mathbf{q}}_{H_{v0}}^{H_0} \otimes \underline{\mathbf{q}}_H^{H_0}.$$

Based on this information, we may then compute $\underline{\mathbf{q}}_{H_v}^{T_v}$:

$$\underline{\mathbf{q}}_{H_v}^{T_v} = \underline{\mathbf{q}}_{H_0}^{T_v}\underline{\mathbf{q}}_{H_v}^{H_0}, \tag{7}$$

where

$$\underline{\mathbf{q}}_{H_0}^{T_v} = \left(\mathbf{q}_{T_v}^{E}\right)^* \underline{\mathbf{q}}_{H_0}^{E}. \tag{8}$$

Finally, it is important to note that, in order to calculate $\underline{\mathbf{q}}_{H_0}^{T_v}$, we do not need to completely describe the relationship between $\mathcal{F}_T$ and $\mathcal{F}_E$. In fact, as we can see in (8), only the rotation $\mathbf{q}_{T_v}^E$ must be specified *a priori*, because the system is invariant with respect to the translational displacement between the robot's torso and the motion tracker.

C. Invariance extended to the other tasks

In the previous section, we developed a reasoning about the need of obtaining an invariance with respect to the physical placement between the robot and the motion tracker. This reasoning was necessary only because the robot's and the human's hands are expressed in different coordinate systems, and it is not practical to find a precise relationship between them. Furthermore, we used the teleoperation task as an example to illustrate how to obtain this invariance.

With respect to the other tasks, the only difference is that, in the initialization phase, we assume that the person is facing the robot, as illustrated in Fig. 4. Hence, $\underline{\mathbf{q}}_{H_{v0}}^{T_v} = \underline{\mathbf{q}}_{R_{v0}}^{T_v}\,\mathbf{q}\,(x,\pi)$, where $\mathbf{q}\,(x,\pi)$ means a rotation of π rad around the x axis. The Algorithm 1 summarizes both the initialization phase and the execution of the cooperation tasks. Note that the initial position of the subject—facing the robot or mimicking it—is given by the parameter $\mathbf{q}_{inv}$. This parameter is not used to describe the task. Instead, it is used only in the initialization, since the robot has no information (in the current configuration of the experiment) about the initial position of the human hand.

[1] Incidentally, our motion tracker provides the the rotation matrix $\mathbf{R}_H^E$—from where we extract the quaternion $\mathbf{q}_H^E$—and the translation vector t_H^E. Then we compose the dual quaternion by means of $\underline{\mathbf{q}}_H^E = \mathbf{q}_H^E + \epsilon\frac{1}{2}\mathbf{t}_H^E\mathbf{q}_H^E$.

Algorithm 1 Cooperation algorithm

`//Initialization`

`Define` $\underline{\mathbf{q}}_{T_v}^{E}$ `accordingly to the configuration between the robot and the Easytrack 500`

$\underline{\mathbf{q}}_{H_0}^{T_v} \leftarrow \left(\underline{\mathbf{q}}_{T_v}^{E}\right)^{*} \underline{\mathbf{q}}_{H_0}^{E}$

$\underline{\mathbf{q}}_{inv} = \begin{cases} 1 & \texttt{if teleoperation} \\ \underline{\mathbf{q}}\left(x, \pi\right) & \texttt{otherwise} \end{cases}$

$\underline{\mathbf{q}}_{H_{v0}}^{H_0} \leftarrow \left(\underline{\mathbf{q}}_{H_0}^{T_v}\right)^{*} \underline{\mathbf{q}}_{R_{v0}}^{T_v} \underline{\mathbf{q}}_{inv}$

`//Cooperation`

while not *end_of_cooperation*

$\quad\underline{\mathbf{q}}_{H}^{H_0} \leftarrow \left(\underline{\mathbf{q}}_{H_0}^{E}\right)^{*} \underline{\mathbf{q}}_{H}^{E}$

$\quad\underline{\mathbf{q}}_{H_v}^{T_v} \leftarrow \underline{\mathbf{q}}_{H_0}^{T_v} \left(\underline{\mathbf{q}}_{H_{v0}}^{H_0} \otimes \underline{\mathbf{q}}_{H}^{H_0}\right)$

$\quad\underline{\mathbf{q}}_{R}^{T} \leftarrow \underline{\mathbf{q}}_{H_v}^{T_v} \underline{\mathbf{q}}_{\text{task}}^{*}$ `//Note that` $\underline{\mathbf{q}}_{H_m} = \underline{\mathbf{q}}_{H_v}^{T_v}$

$\quad\dot{\vec{\theta}}_R = \mathbf{J}_R^{\dagger} \mathbf{K} \left(\underline{\mathbf{q}}_{R}^{T} - \underline{\mathbf{q}}_{R_m}\right)$

end while

V. Experiments

A. Experimental setup

An experimental setup composed by a humanoid robot and a healthy subject was used to validate the cooperative framework proposed in this work. Both the robot and the person use the right arm for the cooperation tasks, as shown in Fig. 4, which also illustrates the main coordinate frames used in the experiments. In our experimental setup, we assume that the motion tracker is on the robot's left, such that

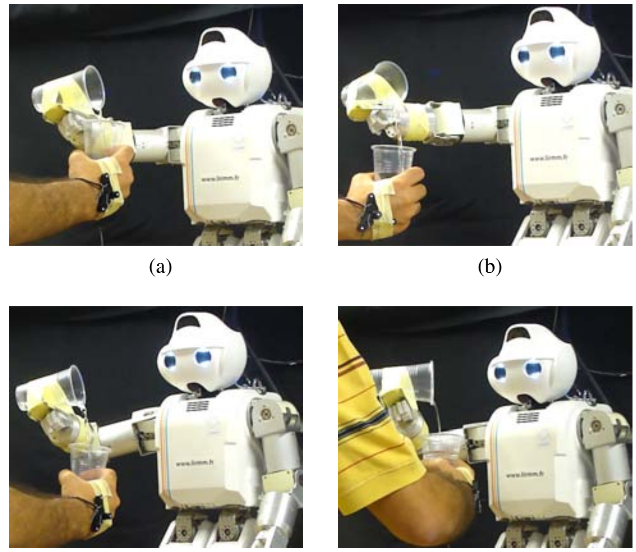
$$\underline{\mathbf{q}}_{T_v}^{E} = \underline{\mathbf{q}}_{T}^{E} = \underline{\mathbf{q}}\left(x, -\frac{\pi}{2}\right). \tag{9}$$

As already mentioned in Section IV-B, the system is invariant with respect to the translational displacement between the robot's torso and the motion tracker. Hence, we do not need to include in (9) the information about the translation.

The robotic platform used in this work is based on the Fujitsu's HOAP3. This small robot is 60 cm tall, weighs about 8 kg and has 28 DOF. More specifically, each arm has 4 DOF. The robot's limited dimensions and restrictions in motion consisted a challenge to the design of illustrative cooperative tasks, but we believe that the platform provided enough versatility to validate the ideas proposed in this work within the chosen set of experiments.

In order to capture human motion, an optical system was used in the experiments. It is an active system based on linear cameras, the Easytrack 500, which produces excellent markers position accuracy. The device provides the marker's pose with respect to its reference frame, $\mathcal{F}_E$. The marker is placed on the subject's hand or wrist, as shown in Fig. 5 and Fig. 6, defining the frame $\mathcal{F}_H$.

In the following section we are going to detail each task separately in order to specify the parameter $\underline{\mathbf{q}}_{\text{task}}$.



(a) (b) (c) (d)

Fig. 5: Task of pouring water.

B. Cooperation tasks[2]

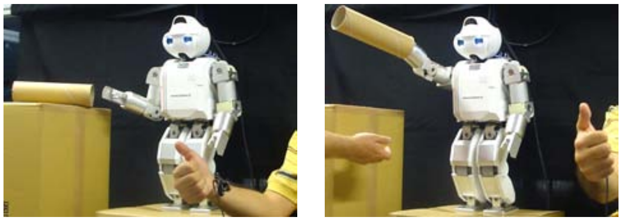
1) Water pouring: In the task of pouring water, the robot must pour the water while the subject handles the glass. Due to the robot's physical limitations, we attached a plastic glass directly in the back of the robot's hand. Since the parameter of the task $\underline{\mathbf{q}}_{\text{task}}$ is given by the geometrical relationship between the hands, using $\mathcal{F}_R$ as reference, we define $\underline{\mathbf{q}}_{\text{task}}$ as being a rotation of π around x_R—enforcing the face to face cooperation—followed by a rotation of $\frac{\pi}{4}$ around z_R. This last rotation actually turns the robot's hand in order to pour the water. On the other hand, the translation was chosen considering the size of the glasses and the initial attachment of the robot's glass. These parameters are summarized in Table I.

We chose different spots, all of them feasible, where the subject had to place his hand. The robot successfully poured the water and was capable of tracking the subject's hand whenever the latter moved. Some of the spots are shown in Fig. 5.

2) Teleoperation: Instead of proposing a new method for teleoperation, which already has been extensively investigated in the literature, the purpose of this experiment is to show that in terms of mathematical description, the teleoperation task can be described similarly to the other tasks presented in this paper. More specifically, since the robot has to mimic the teleoperator, then the parameter of the task is $\underline{\mathbf{q}}_{\text{task}} = 1$. However, the cooperation happens when a second person, the collaborator, interact with the robot. Fig. 6 shows a sequence of teleoperation with cooperation. Using the robot, the teleoperator grabs a pipe and handle it to the collaborator.

3) Simultaneous handling using mirrored movements: In this experiment, the robot acts as a "mirror" of the person

[2]See the accompanying video



(a) (b)

Fig. 6: Teleoperation mode: (a) reaching the pipe; (b) and handing it to another person.

until the object of interest is grasped. From this moment, the robot can help on the manipulation, while keeping the same relative pose which it was performing when the object was grasped. This is a synergistic movement, where the person interacts with the same environment where the robot is.

In order to illustrate this idea, let us consider the following situation. The person must grab an object, but needs help to accomplish the task, because the object is too heavy or too big. This task was already extensively investigated in terms of force control (e.g., [14]), where the robot follows the person by means of force compliance. However, before the activation of the force controllers, the robot should reach the object. If the robot mirrors the person, the person can drive the robot's hand to the right spot while placing his/her own hand.

On the other hand, even if the object is grasped we can still perform force control. For that, we need to analyze the cooperation from a holistic point of view, considering the capabilities of both actors in the interaction. More specifically, even if the robot performs position control, the person could perform force control by positioning carefully the robot and using his/her own force feedback, since the person and the robot are simultaneously manipulating the same object. Fig. 7 illustrates a simultaneous handling where both the robot and the person must grab a pipe.

The parameters of the task are given as follows. Given the initial position of the subject's hand with respect to $\mathcal{F}_{T_v}$—that is, $\vec{t}_{H_0}^{T_v}$—and the new position $\vec{t}_H^{T_v}$, the relative translation is given as $\vec{t}_{\text{task}} = \begin{bmatrix} 0 & 0 & 2\left(x_H^{T_v} - x_{H_0}^{T_v}\right) \end{bmatrix}^T$. It means that when the subject moves his/her hand vertically or horizontally, the robot will try to place his hand at the same place of the subject's hand. However, when the subject move the hand backwards, the robot will also move it hand backwards. Conversely, when the subject move the hand forward, the robot will move it hand forward. Note that, for convenience's sake, we used the displacement along the x axis of the robot's torso as the reference for the z axis of the robot hand. Furthermore, we see that the parameters of this task, differently from the previous ones, is variable.

Fig. 7 shows the sequence obtained from a manipulating task using the mirror mode. First, the system is initialized in the face-to-face configuration. Then, the operator directs his hand towards one extremity of the pipe while simultaneously controlling the robot's hand. Differently from a simple teleoperation, the operator has to take into account both his hand's and the robot hand's poses in order to cooperatively grasp the pipe. After the pipe is handled, the current $\underline{\mathbf{q}}_{\text{task}}$ is stored and from this moment the stored value is used. The purpose is to show that, even if the object is rigid and the robot is controlled by position, the operator can still drive the pipe followed by the robot. This happens because the human arm has more DOF than the robot's arm, and then the operator can exploit his redundancy to maintain the pipe in the same orientation, but changing the orientation of his wrist. In this manner, the robot will try to follow the operator's movement. Moreover, the forces involved in the cooperation are measured by the person's force feedback mechanism, and even if the robot is not capable of performing force control, the human is. Hence, the *human* ultimately takes into account the forces involved in this interaction.

Task	$\underline{\mathbf{q}}_{\text{task}}$
Water pouring	$\vec{t}_{\text{task}} = \begin{bmatrix} 0.01 & 0 & -0.05 \end{bmatrix}^T$ $\mathbf{q}_{\text{task}} = \mathbf{q}\left(x_R, \pi\right)\mathbf{q}\left(z_R, \frac{\pi}{4}\right)$
Teleoperation	1
Simultaneous handling	$\vec{t}_{\text{task}} = \begin{bmatrix} 0 & 0 & 2\left(x_H^{T_v} - x_{H_0}^{T_v}\right) \end{bmatrix}^T$ $\mathbf{q}_{\text{task}} = \mathbf{q}\left(x_R, \pi\right)$

*Note that $\mathbf{t}_{\text{task}} = \left(0, \vec{t}_{\text{task}}\right)$

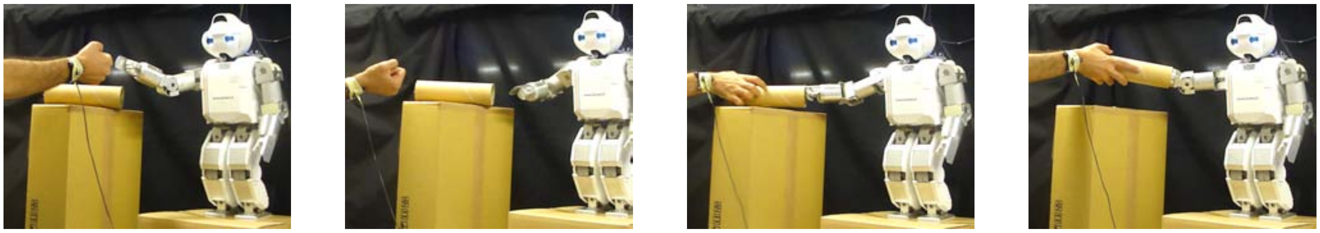
TABLE I: Definitions of the cooperation tasks

VI. Discussion

As we have seen in the previous section, the framework proposed in this work allows us to describe different tasks using the same set of equations. Furthermore, the task's parameter $\underline{\mathbf{q}}_{\text{task}}$ consists of the geometrical relationship between the cooperative hands, and defining the task consists in establishing the desired relationship between the human's and the robot's hands. Moreover, the proposed framework is complementary to force control techniques (e.g., crank rotation), since we can use the relationship between the hands to position them at the right spot.

One interesting observation arose from the experiment of pouring water. Even if the robot acts like a slave, or a "follower", the human ultimately cooperates with the robot. Since the robot has several mechanical constraints, sometimes the task can only be accomplished if the person helps the robot. For instance, being aware of these limitations, people will have the tendency to place the hand where the robot will effectively accomplish the task (or at least where they *believe* that the robot can accomplish it). Another facet in this task is that the robot is regarded as an autonomous entity, which reinforces the collaborative aspect of the task.

In the teleoperation task, even if ultimately the collaboration happens between the collaborator and the operator (whereas the collaborator interacts physically with the robot, the latter is controlled directly by the operator), an effective collaboration will happen only if both collaborator and operator respect the robot's constraints and limitations.



(a) (b) (c) (d)

Fig. 7: Mirror mode: the person control the robot in a collaboration-like fashion. (a) The system is initialized in the face-to-face configuration; (b) the subject's hand is moved backwards. The robot mirrors the movement; (c) the subject drive his hand towards the object, and the robot symmetrically follows the movement; (d) once the object is grasped, the current $\underline{\mathbf{q}}_{\text{task}}$ is stored and remains constant. Since the subject's arm has more DOF than the robot's, the subject can still move the object, followed by the robot.

Furthermore, the robot can be regarded as an extension of the operator's body, since the person regards the robot as separated from his/her own body, but uses the robot to perform the same actions as if he/she were physically located at the same place of the robot's.

The last experiment—and conceptually the more complex—is the simultaneous handling in the mirror mode. In this kind of scenario, the robot cannot be straightforwardly regarded neither as an autonomous entity nor as a human body extension. Since the operator is directly controlling the robot, its status is not of an autonomous entity. On the other hand, the idea of "body extension" cannot be easily applied either, for the robot is mirroring the person instead of mimicking her. Hence, the person has to take into account the simultaneousness aspect of the whole task—controlling the robot while interacting with it by means of the manipulated object.

The remarkable conclusion from the previous discussion is that, even if the tasks illustrated in this paper are conceptually different, mathematically they can be described in the same way, that is, by the relative configuration between the robot's and human's hands.

Using the proposed techniques in this paper—the definition of the task by means of relative configurations, the unified approach for representing and executing the task by means of dual quaternions, and the invariance provided by the decompositional multiplication—a large set of complex tasks can be easily defined and implemented.

Moreover, our formalism is suitable for the integration with whole-body motion frameworks (e.g., [15]), where the cooperation task could be first defined by using (1), and then the robot would continuously perform a whole-body motion in order to achieve the desired relative configuration between the human's and the robot's arms.

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