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# Simulated Framework for Physical Human-Robot Collaboration to Co-manipulate Objects

Martin Mujica<sup>1</sup>, Mourad Benoussaad<sup>2</sup> and Jean-Yves Fourquet<sup>2</sup>

**Abstract**—Physical Human-Robot Interaction (pHRI) is an important field that has grown considerably over the last years. Nowadays, new possible applications are being evaluated. In order to tackle the new issues that might arise, novel methods for robot control have to be used. To ease the comparison and evaluation of those methods, this work proposes a simulated framework to study the collaboration between a robot manipulator and a person while moving payloads. The way of conceiving the simulated framework done in Matlab is presented, detailing how the robot, the object, and the person can be described. Experiments are done on a real robot KUKA LBR iiwa 14 R820 to compare and validate the interaction forces predicted by the proposed framework. Results showed that this method allows to simulate the co-manipulation of objects, even with unknown load, showing forces that are close to the real ones applied by the person. The Matlab code is publicly available at [https://gitlab.com/MMujica/simulated\\_framework.phrc](https://gitlab.com/MMujica/simulated_framework.phrc).

## I. INTRODUCTION

Robotics is a concept that has grown through the years. More recently, the notion of human-robot interaction appeared and is now consolidated as one of the key elements of the future industry [1]. Within this topic, the physical interaction and collaboration between robot manipulators and people is of particular interest [2]. Among the many possible tasks that can be achieved by a person and a robot working together, the co-manipulation of an object is rather promising. The reason can be linked to the fact that in industrial and non-industrial tasks, there is in general an object that has to be manipulated (e.g. a tool, a box, etc). In order to achieve this type of tasks, several challenges have to be overcome, such as the grasping of the object, handling objects with complex geometry or an important load, as well as how to move the object in coordination [3].

The challenge in that context is to allow the robot to behave appropriately and help the person achieve the common goal. For those reasons, innovative approaches have to be used with respect to classical robotics. The common approach to evaluate results is to test those methods with robot manipulators and study the resulting behavior. In general, this implies several difficulties as physical Human-Robot Interaction (pHRI) has an inherent risk for the person [4]. Furthermore, the access to the robot manipulators might be a limitation either by economic reasons or other restrictions (as it happened in several cases due to COVID-19 lockdown regulations). In automation and control, the classical way of dealing with the problem is to simulate the

system beforehand. In the context of robotics this is more challenging, as robots are rather complex elements. In the case of pHRI, this is even more difficult as the person is quite a complex element to model. For these reasons, there is no clear and predefined approach to simulate interaction tasks between a person and a robot.

This problem has also been highlighted in [5] where authors proposed the study of different human-robot interaction scenarios with the MORSE simulator [6]. Other simulators such as Gazebo<sup>1</sup> have been used in robotics, but the simulation of the robot along with the person remains a difficult task. One recent proposal to do it has been presented in [7]. The need of reliable approaches for simulation in the context of human-robot interaction can be found in several applications. For instance, in [8] authors presented the USARSim, to simulate complicated scenarios for mobile robots in the context of search and rescue.

Differently from these works, we propose a simulated framework that focuses on the interaction between a person and a robot manipulator to move objects together. The main difference with other approaches is that this framework concentrates exclusively on the trajectory and interaction forces. It can provide a good approximation of the interaction forces that might appear in a real experimental case while remaining simple (i.e. it is not necessary to handle collisions or physical engines). In summary, instead of dealing with the scenario or other possible abstract layers of interaction, this method focuses on the close interaction between the person and the robot, highlighting velocities and forces that might appear. The advantage would be to allow simulations to evaluate control laws and compare them, before doing experiments or even when these ones cannot be carried out.

The rest of this paper is structured as follows: Section II presents the context of the object co-manipulation task to be simulated. Then Section III introduces the simulated approach proposed to model each element of the collaboration. In order to compare with the real case, Section IV presents the proposed experimental scenario to compare with the simulated framework. The results of these comparisons are shown in Section V along with comments on the capabilities of the proposed approach. Finally, conclusions and perspectives are presented in Section VI.

## II. CONTEXT

The collaboration between a robot and a person can be done at different levels with different elements. In the

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proposed scenario (that we aim at providing a simulated framework), it consists on a redundant robot manipulator with 7 d-o-f used to manipulate an object that is rigidly attached to its end-effector. On the other side of the object, the person can interact to guide and collaborate in translating or rotating the object. A scheme of this scenario can be seen in Fig. 1. The interest behind this scenario is that it allows a comfortable collaboration to handle an object that might possess an unknown and non-negligible load inside.

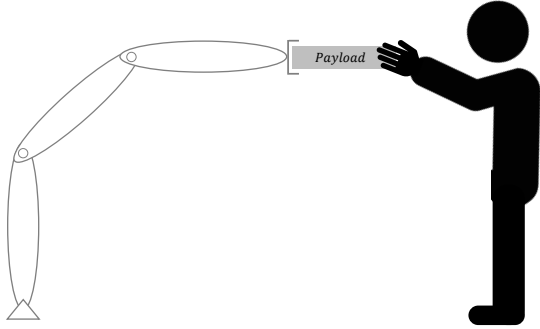


Fig. 1. Scheme representing the robot on the left side, with the object rigidly attached to the end-effector and the person interacting with the object on the other side.

In the presented context, several things have to be considered. First, the load inside the object is considered unknown and thus it cannot be included in the model of the robot. Also, the person is an unpredictable element in the collaboration. Without the use of external sensors (such as cameras), the force and velocity applied by the person are the only source of information available to understand the person’s goal. Within the scenario described, the robot should be able to help the person to move an unknown payload, whenever the person desires to collaborate with the robot. In the following subsections, the scenario is clearly defined, to then detail how it was implemented in simulation in Section III.

#### A. The robot

In this work, a redundant robot manipulator is used. Without losing the generality of the methods proposed, that can be applied to other type of manipulators, a KUKA LBR iiwa 14 R820 is considered. This rather new robot has the particular feature of having position and torque sensors in each joint, making it an interesting option for pHRI tasks. In the context of this work, the robot is considered to be rigidly mounted over a base. No compliance is considered at this level nor movements of the base. The object to manipulate is rigidly attached to the end-effector. This is a strong constraint that was taken since the goal is to have a simplistic framework that focuses on the interaction.

#### B. The object

The considered object is a box attached at the end-effector level. This is a choice for convenience of the experiments as it allows to change the load inside the box. However, the results obtained can be used for other cases such as handling tools or other type of objects. The box is considered to be

rigid (i.e. no inherent flexibility) and its geometry is not modified at any point. The case of flexible objects implies other issues (e.g. the forces on both ends of the object would not be the same). Therefore, in the scope of this work the object to co-manipulate was considered to be rigid. The load and inertia properties of the box are also unaltered, but load is included inside of the box, changing completely the inertia tensor and the gravity force that will appear for the whole object.

#### C. The person

Out of the three elements that participate in the collaboration, the person is the most difficult to model, describe and predict accurately. In the context of this work the person is considered to be standing in front of the robot and interacting with the box from the opposite side. As the robot’s base is static, the person is not moving away from the robot’s workspace and the person is interacting exclusively with the other side of the box (i.e. no contact with the other links of the robot).

### III. SIMULATED FRAMEWORK

This section will cover the simulated framework proposed to study the collaboration within the previously described context. The interest lies in the possibility of obtaining results without the need of the implementation on the real robot. This could allow the evaluation of different control laws and methodologies, perform comparisons and draw conclusions. After doing simulations with this framework, the implementation on a real robot would be safer and more predictable. The following subsections will present the simulated scenario, consisting on the robot, the object and the person along with the control laws applied in simulation.

The setup for simulations involves the model used to approximate the real KUKA iiwa, a simulated object included (where the payload can be modified), and a model that represents the person’s hand in continuous contact with the object. An image of the 3D model can be seen in Fig. 2.

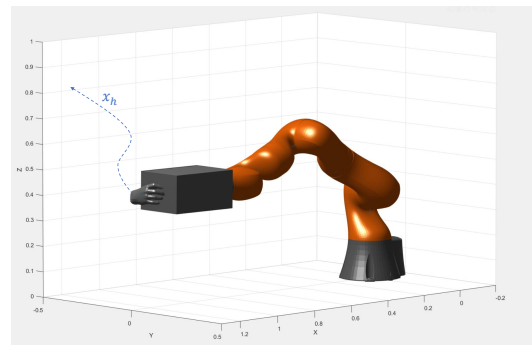


Fig. 2. 3D image of the robot-object-hand simulated in Matlab. The hand is modeled by a spring-damper rigidly attached to the other side of the box.

#### A. Simulated Robot

The robot (as shown in Fig. 2) is described using features of the Robotic toolbox of Matlab, where the model used is the same as in [9].

Without losing generality, as the goal is to present the framework for simulations, an Admittance controller based on [10] is applied. The goal is to obtain the behavior of a mass-damper system defined as:

$$M_d \ddot{x} + K_D \dot{x} = h_e, \quad (1)$$

where  $M_d$  is a positive definite diagonal matrix that represents the desired virtual inertia of the end-effector, while  $K_D$  is also a positive definite matrix representing the damping. The vector  $x$  corresponds to the end-effector's pose, along with its derivatives. Finally,  $h_e$  is a  $6 \times 1$  vector containing the three external forces and the three external torques acting on the robot in the Cartesian space.

### B. Simulated Object

To simulate the box, as we consider it is rigidly attached to the end-effector, it was included as an extra link for the robot with a fixed joint. An image of the robot with the box attached to the end-effector can be seen in Fig. 2. Then, when a new load is included in the box, inertia properties of the new extra link included are modified (but not the model that is used for the control of the robot). In summary, two models are considered, a real one with the unknown load included (the one simulated) and another one without the load, that is used in the controller of the robot.

The load included will be varied and represent a few kilograms. The extra load is considered to be concentrated at the center of gravity of the box. In the model to be simulated, the mass of the new extra link is modified to include the new mass and inertia tensor whenever the load is included.

### C. Simulated Human

As mentioned, the person is considered standing in front of the robot, meaning that the hand is considered the element of collaboration with the box as presented in Fig. 2.

In order to simulate the person's interaction, the human hand was considered as a punctual element with the dynamics of a spring-damper. This approach considers the end-point stiffness and damping of the real person, other approach could be to consider the full arm as a kinematic chain. This was not done to avoid an extra complexity in simulations, considering that the person's interactions are mainly described by the forces applied and the velocities at the end-effector level. Then, the dynamic of the person is considered to be:

$$K_{D_h} (\dot{x} - \dot{x}_h) + K_{P_h} (x - x_h) = -F_h, \quad (2)$$

with  $x_h, \dot{x}_h$  being the trajectory to be followed by the person (and unknown for the robot),  $K_{D_h}$  and  $K_{P_h}$  the damping and stiffness matrix for the person in the Cartesian space. Then,  $F_h$  is the force produced by the spring-damper, meaning its the force applied by the person on the robot. For that reason the negative sign appears, leading to the fact that  $F_h = h_e$  while in continuous contact. Moreover, the values for the matrices can be obtained from several studies of the human's arm end-point stiffness, such as: [11], [12], [13]. In these studies, the resulting end-point stiffness

present important variations depending on the method used, the task to fulfill or the experience of the person. In this work we consider the matrices as:<sup>2</sup>  $K_{P_h} = \text{diag}_6\{176\}$  and  $K_{D_h} = \text{diag}_6\{19\}$  based on the average results for the naive person in Z direction of [13]. A representation of the model of the person collaborating with the robot is presented in Fig. 3.

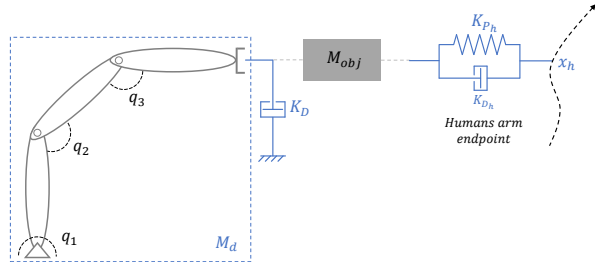


Fig. 3. Scheme of the robot controlled as a mass-damper attached to the box with unknown load. On the other side of the box the person, represented by a spring-damper is rigidly attached and following a predefined trajectory.

As for the trajectory to be followed, there are different possibilities. To compare the simulation with the experimental case, the same trajectories done experimentally are used for the sake of the comparison. However, for using the simulated framework without the need of the experimental robot, a trajectory has to be proposed. In this work we propose soft point-to-point movements with bell-shaped velocity profile as presented in [14]. For instance, an example of a back and forth movement in the X-axis is shown in Fig. 4. The advantage is that it represents closely the movement of a real person in point-to-point movement.

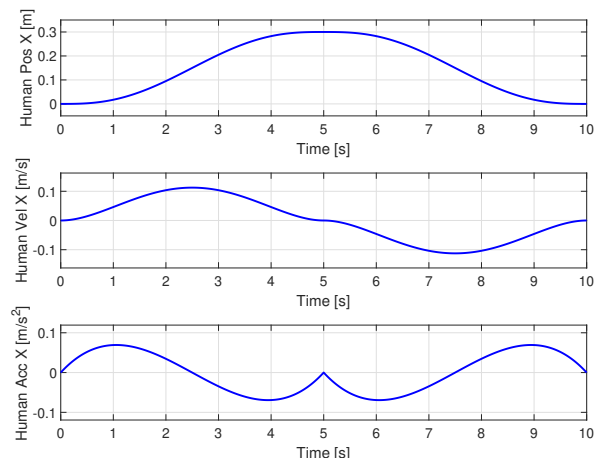


Fig. 4. Position, velocity and acceleration profile of the soft point-to-point movements with bell-shaped velocity curve used.

## IV. EXPERIMENTAL SETUP FOR VALIDATION

A simulated scenario for pHRC, particularly for object co-manipulation, was presented in Section III. As mentioned,

<sup>2</sup> $\text{diag}_i\{\cdot\}$  is a function that produces a  $i \times i$  diagonal matrix with the elements of the diagonal defined as the input vector, or as a repetition of the scalar input, with  $i \in \mathbb{N}$

in robotics, and particularly for interaction, the experimental cases are used in general. To evaluate the usefulness and the reliability of our simulated approach, in comparison to the real case, several experiments are done on a real Kuka LBR iiwa 14 R820.

This section presents a general overview of the experimental setup for the object co-manipulation tasks. The goal is to represent the same case as the one detailed in Section II and applied in simulations in Section III. The experiments were carried out with the robot Kuka LBR iiwa 14 R820 with a box rigidly attached to its end-effector to allow for more load to be added inside. As in the simulated scenario the interactions forces between the person and the box were considered known, a six axis F/T sensor RFT76-HA01 from Robotous<sup>3</sup> was attached at this point. The setup with the F/T sensor attached to the box, on the opposite side of the robot can be seen in Fig. 5. The person can directly interact at this level by manipulating the handle of the sensor as done in other works such as [15], [16]. The robot was

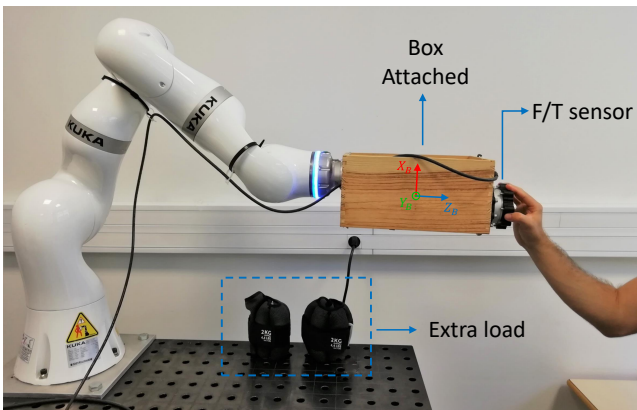


Fig. 5. Setup of the Kuka iiwa 14 R820 robot with the box and the sensor attached. The person is able to manipulate the handle of the sensor to move the robot and to include the unknown load inside the box.

controlled using the *Fast Robot Interface (FRI)* system provided to work under real time constraints. It consists on a predefined architecture, provided by Kuka which allows the communication between the robot and an external client program, in another computer, with cycles of up to 1 ms. Since data obtained from the robot through *FRI* is limited (e.g. inertia matrix, Jacobian and end-effector's pose are not provided), KDL library<sup>4</sup> for kinematics and dynamics has been used for the design of the proposed controller. The model of the robot was obtained from [9] and implemented in KDL.

The box used is rigidly attached to the robot at the end-effector level. Its dimensions ( $l_{B_x}$ ,  $l_{B_y}$ ,  $l_{B_z}$ ) and mass  $m_B$  were measured and used to estimate the inertia with respect to its center of gravity (considered at the center of the box). For the inertia tensor, given the shape of the object, only the diagonal elements were considered ( $I_{B_{xx}}$ ,  $I_{B_{yy}}$ ,  $I_{B_{zz}}$ ). These parameters are all presented in Table I

<sup>3</sup><http://www.robotous.com>

<sup>4</sup><http://www.oroocos.org/wiki/orocos/kdl-wiki>

TABLE I

MASS, DIMENSIONS AND INERTIA PARAMETERS OF THE BOX ATTACHED TO THE END-EFFECTOR OF THE ROBOT WITHOUT LOAD INSIDE.

$m_B$	$l_{B_x}$	$l_{B_y}$	$l_{B_z}$	$I_{B_{xx}}$	$I_{B_{yy}}$	$I_{B_{zz}}$
0.941	0.15	0.2	0.3	0.0238	0.0176	0.0106

The dimensions and inertias are written with respect to the box frame shown in Figure 5 and in SI units. The box along with all these parameters were included in the model as an extension of the last link. Same considerations were done for the F/T sensor. Finally, during the experiments, changes in the payload are considered. This was done by including different loads inside the box that were rigidly attached to avoid movements. It is important to note that the extra load is not considered in the robot model for the control design nor in the robot side of the controller for gravity compensation. In consequence, the extra load is completely unknown for the robot's controllers, as it was done in simulations

## V. RESULTS AND DISCUSSION

In this section, the simulated framework for object co-manipulation proposed is evaluated. As it is not a new simulated engine but rather a novel framework to simulate close pHRI, comparisons with other methods of simulation are not straightforward. Instead, we evaluated it experimentally by comparing with the real-case scenario. The goal is to evaluate its accuracy and reliability to represent the real case, along with its limitations. To do so, in this section we compare the results obtained with the simulated framework with experiments done with the same controller but in a real co-manipulation scenario.

The simulated scenario was developed in Matlab<sup>5</sup> and Simulink using a computer Dell<sup>6</sup> *Precision 3520* with a processor i7, 2.90 GHz and 16GB of RAM. The operating system used is a 64 bits Microsoft Windows 10<sup>7</sup>.

To ease the comprehension of the results, the forces measured by the F/T sensor in the experimental case are denoted as  $F_{h_{exp}}$  while the forces acting on the simulated robot (equals to the generated by the simulated model of the person) are denoted as  $F_{h_{sim}}$ . As for the trajectories described, the poses of the experimental robot (considered at the contact point with the person) are described by  $x_{exp}$ , while the poses of the simulated robot (again, at the contact point with the person) are denoted  $x_{sim}$ . Finally, the trajectory used for the simulated model of the person, see (2), (that is considered as the reference intended to be followed by the model of the person, as shown in Fig. 3) is denoted  $x_h$ .

In this section, three different simulations are done to illustrate different features of the simulated framework:

- **Use of the experimental trajectory for the simulated person:** The movement is done by the real person in

<sup>5</sup>[www.mathworks.com](http://www.mathworks.com)

<sup>6</sup>[www.dell.com](http://www.dell.com)

<sup>7</sup>[www.microsoft.com](http://www.microsoft.com)

the experimental scenario obtaining the trajectory  $\mathbf{x}_{exp}$ . This real trajectory  $\mathbf{x}_{exp}$  is directly used in simulations as  $\mathbf{x}_h$ . Then, the simulated person intends to perform a trajectory  $\mathbf{x}_h$ , while attached to the robot, producing the trajectory done in simulation  $\mathbf{x}_{sim}$ . The goal is to have the trajectories as close as possible to compare the efforts obtained in both cases.

- **Include the unknown load in the box:** Similar case than the previous one, but including the extra unknown load in the real experiment and in simulations, to analyze and compare the behaviors.
- **Use of the polynomial trajectories for the simulated person:** The movement is done by the real person in the experimental scenario obtaining the trajectory  $\mathbf{x}_{exp}$ . Based on the displacement done and time for the movement, the simulation is adjusted but using the polynomial point-to-point movements for the simulated person  $\mathbf{x}_h$ . Then, the simulated person intends to perform a trajectory  $\mathbf{x}_h$ , while attached to the robot, producing the trajectory done in simulation  $\mathbf{x}_{sim}$ . This allows for a simulation that does not depend on the use of the real robot.

#### A. Use of the experimental trajectory for the simulated person

In this part, the trajectories done by the real person are used for the simulated person. The goal is to have two similar movement in order to analyze the efforts obtained in simulation with respect to the real ones done by the person. Then, the real trajectory done by the person and the robot in the experimental case ( $\mathbf{x}_{exp}$ ), is applied in simulations for the person's desired movement ( $\mathbf{x}_h$ ). The results can be seen in Fig. 6. Since  $\mathbf{x}_h$  is equal to  $\mathbf{x}_{exp}$ , only  $\mathbf{x}_h$  is shown in the figures.

The results obtained show that simulated forces are close to the real ones done by the person. This simple approach for simulations allows to predict closely the interaction forces that would appear in a real collaborative scenario. It is important to notice that as it can be seen in both examples, the trajectories done experimentally ( $\mathbf{x}_{exp}$ ) and the ones done in simulation ( $\mathbf{x}_{sim}$ ) differ. The reason is that the experimental trajectories done by the robot are used as the "desired" trajectories for the person in the simulations and, as the person is modeled as a spring-damper in simulations, the resulting trajectory done in simulation ( $\mathbf{x}_{sim}$ ) will differ from the other two. The difference will depend on the stiffness and damping terms of the person.

#### B. Including the unknown load in the box

One interesting issue in object co-manipulation is the load of the object, specially when it is unknown. Therefore, a comparison is done of the Admittance controller for simulations and experiments but with an unknown load of 1.5 kg. Then, results can be seen in Fig. 7. The movements done in this cases are slightly different from the ones shown before as the unknown load affects the movements done by the person. However, the simulated and experimental forces are

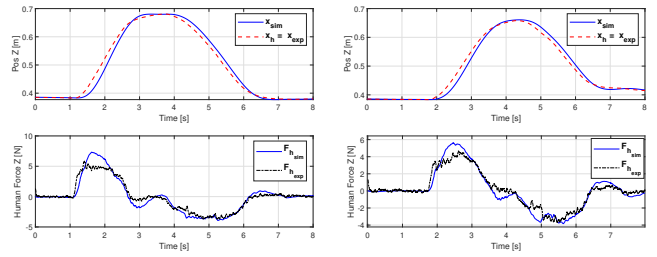


Fig. 6. Two examples of experiments to compare the simulated  $\mathbf{x}_{sim}$  and experimental  $\mathbf{x}_{exp}$  trajectories described in the Z-axis, when the person is guiding the robot. The simulated person  $\mathbf{x}_h$  follows the trajectory done experimentally  $\mathbf{x}_{exp}$ . The bottom images presents the human's forces applied in the Z-axis for the simulated and experimental cases.

quite closer. These results show that the proposed model can also be used to analyze the cases of unknown objects being co-manipulated.

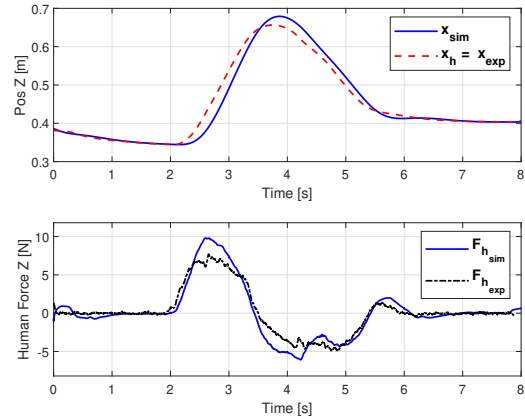


Fig. 7. Comparisons between simulated and experimental implementation for a trajectory in the Z-axis but with a load of 1.5 kg inside the box. The top image presents the trajectory done by the robot in simulation and in the experiments. The bottom image presents the human's forces in the Z-axis for both cases.

Furthermore, it has been shown that using a spring-damper system to model the person manipulating the box represents qualitatively the real phenomena of the object co-manipulated by the real person and robot. Then, it is remarkable that, simulated results represented quite closely the interaction forces of the real experiment. It is important to highlight that the stiffness parameter used for the person (that is not the subject of study in this work) affects the results. Therefore, with improved values for the person's parameters, results could be even closer to the real ones in the collaborative scenario.

#### C. Use of the polynomial trajectories for the simulated person

The previous results have shown that if the trajectories done in simulation and experiments are close, the interaction forces predicted by our approach represent closely the real ones. However, the main goal of this method is to allow the simulation of the experimental case, without the need of the real robot. Therefore, in this subsection, the polynomial trajectories shown in Fig. 4 are used for the desired trajectory

of the person  $x_h$  in the simulated framework. Only for comparison of the results obtained, the trajectories are also done experimentally. Since in a collaboration it is not feasible to impose a precise movement to the real person, the trajectories are done first in the real experiment by the person and then replicated in similar conditions (amplitude of the movement, duration) in simulation, with the polynomial point-to-point movements.

As done before, the results are presented in pairs to improve the confidence of the results. In Fig. 8 two examples are given where the person performed a trajectory in the Z-axis. As expected, there are some differences in the displacement as the polynomial trajectory does not represent exactly the movement done by the person. However, this rather simple framework allows for a fair representation of the movement and, particularly, of the forces applied by the person (as it can be seen in the images on the bottom). Despite some quantitative differences, the behavior in simulation and experiments is similar. Negative forces appear in both figures when the person intends to stop the box (around  $t = 3$  s) in simulation and in experiments, showing the fidelity of the simulations. It is clear that the simulations cannot represent perfectly the experiments, and more difficult movements or changes in the person stiffness would degrade the results. Nevertheless, this very simplistic framework allows to evaluate the control laws beforehand in a collaborative scenario, obtaining results that represent closely the ones of the experiments.

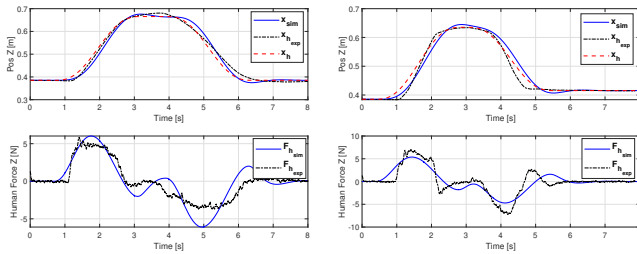


Fig. 8. Two examples to compare the simulated  $x_{sim}$  and experimental  $x_{exp}$  trajectories described in the Z-axis, when the person is guiding the robot. The simulated person  $x_h$  intends to follow a polynomial trajectory. The bottom images presents the human's forces applied in the Z-axis for the simulated and experimental cases.

The advantage of this framework, as presented in this subsection, is that the control laws can be easily evaluated and compared for a co-manipulation scenario without the need of the real manipulator. The results show that the framework allows a comparison to obtain, at least, qualitative results to compare different methods or control laws (without the need of a person and the risks of an experimental application).

## VI. CONCLUSIONS

This work presented a simulated framework to represent closely the behavior of a person co-manipulating an object with a robot manipulator. The approach to represent the robot, the object and the person, along with their interactions are presented. Comparisons are done between this approach

and an experimental scenario with a real robot to evaluate the accuracy of our method. Results showed that the simulations emulate correctly the real behavior, allowing the simulations to be used before moving to a real implementation. Despite the closeness of the results there are certainly some differences between simulation and experiments. These differences could be due to the fact that the reaction from the person to the robot's movement cannot be represented with our simulated framework. For those reasons, in future works the stiffness will be variable to better represent the person's adaptability during the task.

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