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► **To cite this version:**

Antoine Bussy, Abderrahmane Kheddar, André Crosnier. Human-Humanoid Coworker in a Beam Transportation case. RSJ: Conference of the Robotics Society of Japan, Sep 2012, Sapporo Convention Center, Japan. lirmm-00808349

**HAL Id: lirmm-00808349**

**<https://hal-lirmm.ccsd.cnrs.fr/lirmm-00808349>**

Submitted on 5 Apr 2013

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# Human-Humanoid Coworker in a Beam Transportation case

Antoine Bussy \*Abderrahmane Kheddar André Crosnier

## 1. INTRODUCTION

When two humans perform the transportation of an object together, such as a table, they are able to guess the other partner's intentions and act accordingly. The mutual understanding of each partner's intentions by the other generates *proactive* behaviors and good synchronization of the dyad during the task. Moreover, both partners may alternatively share the leadership of the task during its execution and take decisions such as turning or stopping, relying on the information they get. Because one might know and/or perceive something the other does not, a share of the leadership is desirable [1]. These are two characteristics we want to reproduce with a humanoid robot performing such a task with a human partner (see illustration on Fig. 1): *proactivity* and *role switching*.

Relatively to existing work, our approach distinguishes in its capability to guess the human partner's intentions for a wide variety of motions, where [2] only considers point-to-point movements. Furthermore, we distinguish the recognition of the partner's intended trajectory from the action undertaken to help him/her. Our proactive follower acts similarly to a leader. The difference is that it chooses to follow a trajectory determined from a guess of its partner's intentions rather than from its own volition. Thus our approach allows a natural role switching. We proposed a simpler one-degree-of-freedom control law based on a study performed with human subjects in [3] and this article generalizes it.

In Section 2., we propose a compliant position control law for both leader and follower modes and how it can be used for role switching. We describe how a motion decomposition allows to recognize various intended trajectories in Section 3.. We present how a human operator takes the control of the robot in the leader mode with a joystick in Section 4. and we test our control scheme in Section 5. by making our HRP-2 humanoid robot perform the transportation scenario of Fig. 1 with a human partner.

## 2. Trajectory-based Control Law for pHRI

In the following, we suppose that every manipulator controls the same point of the transported object which we call *the manipulation point*. Because the object is rigid and the manipulators firmly hold the object, controlling the manipulation point position and orientation is equivalent to controlling the object trajectory.

### 2.1 Proposed Control Law

In this section, our goal is to control the Cartesian position and orientation of the manipulation point, while maintaining a safe physical interaction with the human partner. We propose the following simple trajectory-

referenced admittance control law [4]:

$$\mathbf{F} = M(\ddot{\mathbf{X}} - \ddot{\mathbf{X}}_d) + B(\dot{\mathbf{X}} - \dot{\mathbf{X}}_d) + K(\mathbf{X} - \mathbf{X}_d) \quad (1)$$

where:

- $\mathbf{X}$  is the manipulation point trajectory,
- $\mathbf{X}_d$  is the manipulation point desired trajectory,
- $\mathbf{F}$  is the force sensed on the manipulation point,
- $M$ ,  $B$  and  $K$  are constant inertia, damping and stiffness matrices computed at the manipulation point.

### 2.2 Behavior in Collaborative Mode

Here, we assume that the forces applied by the other partner in collaborative mode cannot be predicted. However, we show that there is an alternative method to achieve a common desired trajectory. All the reasoning described in this subsection can be straightforwardly extended to several partners. The notations of the previous subsection are reused, indexed with the number of the partner  $i \in \{1, 2\}$ .

Applying (1) for each partner, we obtain the following object dynamic equation

$$m\ddot{\mathbf{X}} = \sum_{i=1}^2 M_i(\ddot{\mathbf{X}}_{d,i} - \ddot{\mathbf{X}}) + B_i(\dot{\mathbf{X}}_{d,i} - \dot{\mathbf{X}}) + K_i(\mathbf{X}_{d,i} - \mathbf{X}) \quad (2)$$

where  $m$  is the object inertia transported at the manipulation point. For the sake of clarity, we assume that the human/robot control law is the one we propose. In the case where

$$\mathbf{X}_{d,1} = \mathbf{X}_{d,2} = \mathbf{X}_d \quad (3)$$

and if we consider the object inertia as a perturbation, the realized trajectory is  $\mathbf{X}_d$ . In practice, we would rather have

$$\begin{cases} \dot{\mathbf{X}}_{d,1} = \dot{\mathbf{X}}_{d,2} = \dot{\mathbf{X}}_d \\ \mathbf{X}_d = (K_1 + K_2)^{-1} [K_1\mathbf{X}_{d,1} + K_2\mathbf{X}_{d,2}] \end{cases} \quad (4)$$

The position offset between  $\mathbf{X}_{d,1}$  and  $\mathbf{X}_{d,2}$  results in a constant co-contraction force between partners which is observed in [5].

As different desired trajectories results in internal (i.e. not working) forces exerted by the two partners, both partners must have the same desired trajectory [1]. This statements is already well-known and predicting a human partner's desired trajectory is one of the main challenges in the pHRI field. However, how  $\mathbf{X}_d$  is determined is completely independent of our control law, so that it can be used in both standalone and collaborative modes (leader and follower). The difference between these modes lies in the trajectory planning of  $\mathbf{X}_d$ . In the case of a proactive follower behavior,  $\mathbf{X}_d$  must be planned to match the human partner's intentions at best.



**Fig.1** Scenario of the experiment. The human-robot dyad has to carry the table through two doors that form a 90° angle. The dimensions of the table are too big to perform the task with a single bend, so that the human has to pass backward through the first door and forward through the second one. The human assumes the leadership of the task as he is walking backward through the first door, and then is guided by the robot through the second door. During this second phase, the robot is remotely controlled by a second human thanks to a joystick.

Besides, assuming we have trajectory planners for each of the three modes (standalone, leader, follower), it is possible to switch the robot behavior as theorized in [1] by switching the planners, without changing the control law that regulates the physical interaction.

### 3. Proactive Trajectory Planner

To be proactive, the robot first needs to correctly guess the human partner’s intentions, and thus to locally predict his/her intended actions or trajectories. The most famous example is the minimum jerk model [2]. However this model is always rather applied to point-to-point motion and does not fit for motions going beyond the reach of the arm or even to motion for which the target point is not well defined. When two humans perform a transportation task of an object, they might talk to give each other indications, such as “turn left”, “go forward” or “stop”. Based on this observation, we suggest to decompose the motion in phases.

The purpose of this part is to generate a plan for the robot in the form of a desired trajectory  $\mathbf{X}_d$  that matches the human partner’s intentions.

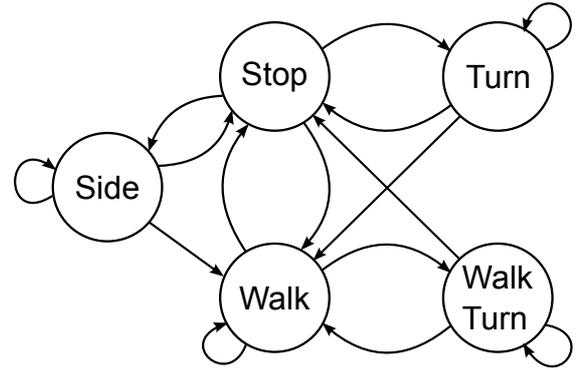
#### 3.1 Motion Primitives

We decompose the motion into template sub-motions, or *motion primitives*, pictured in Fig. 2:

- **Stop:** no motion;
- **Walk:** walk forward or backward;
- **Side:** walk sideways;
- **Turn:** turn on itself;
- **Walk/Turn:** turn while walking forward or backward.

Sequencing these primitives allows to generate various motions, while preventing some unnatural motions like walking in diagonal, i.e. **Walk/Side**. Moreover, we do not allow every sequence. Each primitive is associated with a three dimension velocity vector  $\mathcal{V}$  in a local frame<sup>1</sup> (frontal, lateral and angular velocities) which is updated at each transition. The signal  $\mathcal{V}$  is piecewise constant over time and therefore does not represent a feasible

<sup>1</sup>This frame has the same orientation as the robot but has a fixed origin in the world frame.



**Fig.2** Finite State Machine describing the possible primitives sequencing. It can generate sequences for both leader and follower modes. The transitions are triggered differently depending on the chosen mode.

trajectory. It should rather be considered as a simplified velocity plan. The velocity steps need to be smoothed into a more human-like motion, therefore the local desired velocity  $\mathbf{V}_{d,l}$  is generated from this plan by using a critically damped second order filter

$$\frac{\mathbf{V}_{d,l}}{\mathcal{V}} = \frac{\omega_0^2}{(s + \omega_0)^2} \quad (5)$$

where  $\omega_0$  characterizes the rise time of the desired trajectory.

Then, a change of frame is performed on  $\mathbf{V}_{d,l}$  to get the desired velocity  $\mathbf{V}_d$  in the global frame  $(x,y,yaw)$ . As we only consider planar motions, the vertical component, as well as the roll and pitch ones, are set to zero to obtain a six components vector. Finally,  $\mathbf{V}_d$  is integrated into the desired trajectory  $\mathbf{X}_d$  in the global frame.

#### 3.2 Reactive Generation of Primitives Sequences

In our approach, predicting the leader’s intended trajectory consists in determining a primitives sequence that matches it. We mainly use velocity thresholds to detect the switches of primitives. For example, when the current primitive is **Stop** and the effective velocity  $\mathbf{V}$  of the object is zero, the robot senses a force on its wrists and updates

$\mathbf{V}$  with (1). If the first component of  $\mathbf{V}$  exceeds a given threshold, the robot switches to the primitive **Walk**. We also add high force thresholds, which are tuned to be less reactive than the velocity ones. Self-transitions are also regularly triggered to update  $\mathcal{V}$ , e.g. every second, with the current velocity  $\mathbf{V}$  of the object, so that the robot is able to adapt its desired velocity.

#### 4. Switch to Leader Mode with a Joystick

As stated in Section 2., our pHRI control law is independent of how the desired trajectory  $\mathbf{X}_d$  is generated and thus allows easy role switching between follower and leader behaviors. To demonstrate the capability of our control scheme to do so, we generate an intended trajectory  $\mathbf{X}_d$  for the robot from a joystick. Thus a second human can pilot the robot during the task of transporting the table with the first human partner.

We use a joystick with a digital directional touchpad to control the robot in leader mode. We use the same FSM as in the follower mode (Fig. 2), where the transitions are triggered by the touchpad state instead of haptic clues, thus determining the motion direction. The velocity amplitude is set constant and not controlled by the joystick. The output plan  $\mathcal{V}$  from the FSM is then used the same way it is in Section 3. to compute the desired trajectory  $\mathbf{X}_d$  for the impedance control. The joystick operator can assume or give up the leadership of the task by pressing a specific key on the joystick. The minimal input we use from the joystick and the unnecessary force feedback assess the robustness of our control scheme.

### 5. Experimentation on the HRP-2 Humanoid Robot

#### 5.1 Scenario

To validate our proposed control scheme, we realize the scenario described in Fig. 1.

#### 5.2 Whole Body Motion and Walking

The HRP-2 humanoid robot interacts with its environment through two force-torque sensors mounted on each wrist that measure two forces  $\mathbf{F}_L$  and  $\mathbf{F}_R$ , that we transport at point  $\mathbf{X}$  and sum to get the force feedback  $\mathbf{F}$  for the admittance controller. The stiffness  $K$ , damping  $B$  and inertia  $M$  coefficients are experimentally tuned. The admittance controller output  $\mathbf{X}$  is used to position-control the hands through the Stack-of-Tasks (SoT) developed in [6], a generalized inverted kinematics. The SoT allows to define various tasks –positioning the hands in the world frame in our case– and uses the robot redundancy to realize them simultaneously.

For the locomotion, we used a modified version of the walking Pattern-Generator (PG) developed in [7]. The PG generates on-line a trajectory for the Center of Mass (CoM) of the robot as well as trajectories for the feet, that are also executed through the SoT. The PG takes a 3D desired CoM velocity as an input: two translation and one angular velocities. We regulate this velocity input with a proportional controller so that the relative position of the

robot’s CoM and hands stays constant, as well as the relative orientation of its feet and hands.

### 5.3 Results

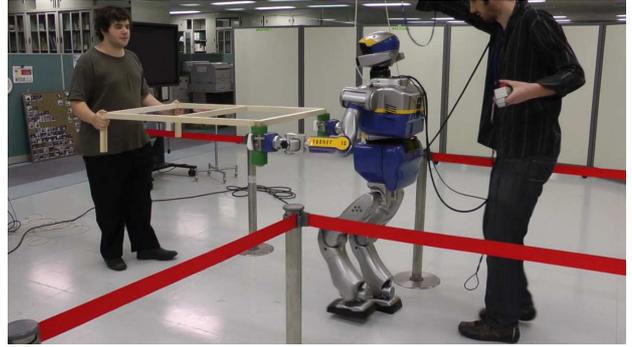


Fig.3 HRP-2 realizing the transportation task with a human partner.

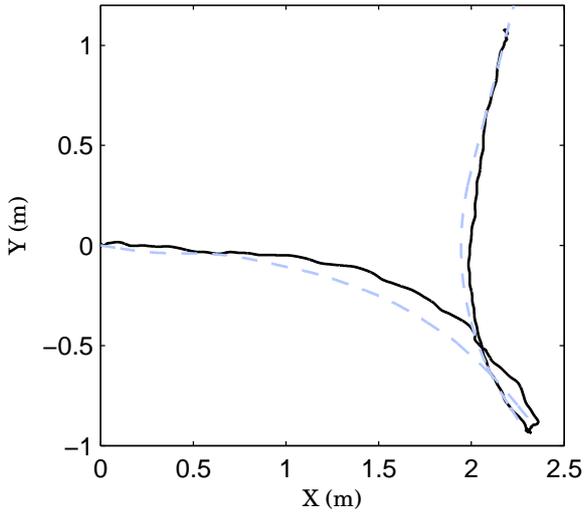
As pictured in Fig. 3, our robot successfully performed the proposed scenario with a human partner. Trajectories  $\mathbf{X}$  and  $\mathbf{X}_d$  are shown in Fig. 4. Their corresponding velocities on the frontal axis – the direction of the motion – are shown in Fig. 5. Forces applied by the robot on the object on the frontal axis are shown in Fig. 6. We can observe that although the robot’s plan  $\mathbf{X}_d$  roughly approximates the object’s effective trajectory, the force applied on object by the robot is greatly reduced compared to a fully passive behavior during the follower mode (until  $t = 20s$ ). Note that during the follower mode, the robot applies negative mechanical power on the object. Around  $t = 12s$  the robot wrongly detects an intention to stop from the leader, but is able to quickly recover and start off again. It results in a high peak in the force profile. Such a misunderstanding might also happen with a human/human dyad.

At around  $t = 20s$ , the joystick operator takes over the control on the robot and completes the scenario. And the human partner is able to follow the robot. The interesting point is that during the second part of the scenario, the force applied by the robot on the object and the velocity of the object have the same sign. The robot applies positive mechanical power on the object, and therefore the human partner applies negative power at constant velocity. Moreover, the leader phase’s force intensity is similar to the follower phase’s, which shows that our implementation of the robot’s follower behavior yields similar results to the human partner’s performance as a follower, force-wise at least.

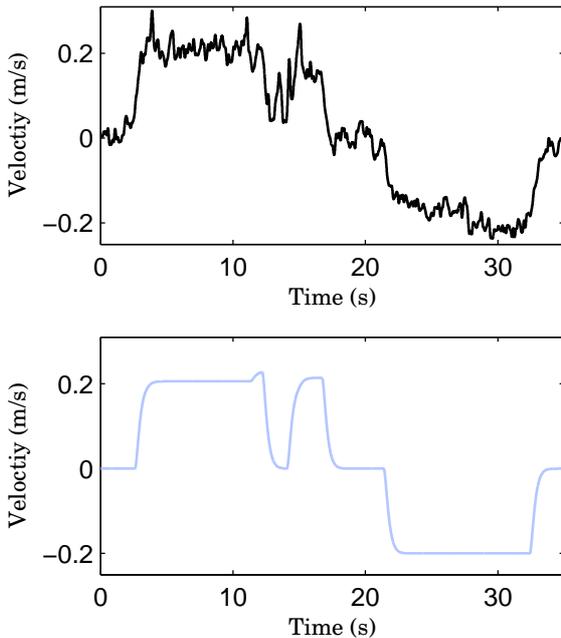
### 6. Concluding Remarks

In this paper, we propose a complete control scheme that allows our HRP-2 robot to perform a transportation task with locomotion, jointly with a human partner.

The first main contribution is the ability of our control scheme to produce a proactive follower behavior. Thanks to a decomposition of the task in sub-motions, the robot is able to guess the human partner’s intended trajectory that leads to a substantial reduction of the workless interaction



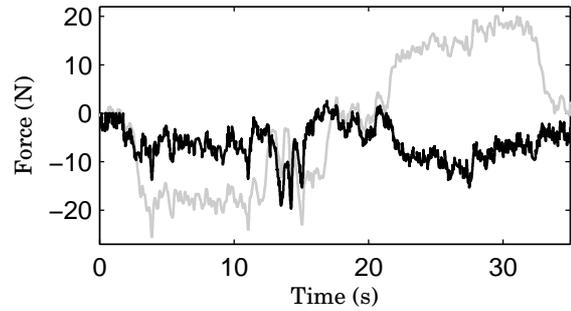
**Fig.4** Trajectories of the object in the XY plan: the admittance controller output  $\mathbf{X}$  in black, follower desired trajectory  $\mathbf{X}_d$  in dotted light blue. The transportation starts at (0,0) and ends around (2,1). The role switching occurs when the object is around (2.3,-1).



**Fig.5** Velocities of the object on the robot's frontal axis: the admittance controller output  $\dot{\mathbf{X}}$  in black (top), robot desired velocity  $\dot{\mathbf{X}}_d$  in light blue (bottom). The role switching occurs at around  $t = 20s$ .

force. Its amplitude is similar to the one observed when the human partner acts as a follower. Our results are similar to the ones obtained in [2] with a similar approach, but allows performing a wider variety of motions.

The second important contribution is the possibility to switch between the follower and leader behaviors in the course of the task. The next step in this domain is to find



**Fig.6** Force applied by the robot on the object (black) on the robot's frontal axis. The gray curve represents the damping part of the interaction force  $\mathbf{F} = -B\dot{\mathbf{X}}$ : it is the force that would be applied by the robot with a passive behavior. The role switching occurs at around  $t = 20s$ .

a method to reactively generate a leader plan for the robot and how and when to automatically switch between the two modes.

Our approach can be made more complex with additional primitives to widen the possible motions and tasks. We are thinking about primitives that allow precise positioning of the manipulated object, which we are not considering in our transportation task. It can also be generalized to completely different tasks if one can find a good decomposition of the task in elementary subtasks and a method to determine the switch timings between these subtasks.

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