Mapping Human Intentions to Robot Motions via Physical Interaction Through a Jointly-held Object

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***Abstract*— In this paper we consider the problem of human-robot collaborative manipulation of an object, where the human is active in controlling the motion, and the robot is passively following the human's lead. Assuming that the human grasp of the object only allows for transfer of forces and not torques, there is a disambiguity as to whether the human desires translation or rotation. In this paper, we analyze different approaches to this problem both theoretically and in experiment. This leads to the proposal of a control methodology that uses switching between two different admittance control modes based on the magnitude of measured force to achieve disambiguation of the rotation/translation problem.**

I. INTRODUCTION

A recent trend in both industrial and domestic robotic applications is to let humans and robots cooperate by jointly manipulating a common object. Typically, the robot provides help to lift or stabilize a heavy or cumbersome object, while the human provides directions on how the object should be moved. This also includes kinesthetic teaching scenarios, where the human instructs the robot by explicitly demonstrating the object motion, until the robot is able to perform the task autonomously, as illustrated in Fig. 1.

Assuming that safety concerns are properly addressed, the main enabling technology needed to implement such robots is a control system that can understand and adapt to the motion desired by the human operator. Traditionally, this has been done by utilizing different types of impedance or admittance controllers [1]–[3] that decrease the appearant mass of the object, so that the human can move it freely by applying forces for translation and torques for rotation. However, with large or massive objects, that the human may possibly only be able grasp with one hand, there may be significant limits to the amount of torque that the human can apply directly to the object, in practice only allowing the human to robustly control the applied force. In such a scenario, the control space of the human is of lower dimension than the state space of the object, and the problem of resolving the desired object motion from the applied force arises, specifically formulated as the ambiguity of whether rotation or translation is desired.

The main contribution of the present paper is a new analysis of the rotation/translation problem, and the design and evaluation of a control framework that is able to understand human intention for translation or rotation and generate the proper motion, resulting in efficient manipulation according to the human intention.

The paper has the following structure: Section II reviews the state of the art in related work, Section III formalizes the problem, Section IV describes the experimental evaluation on a set of human-robot comanipulation tasks. Finally, conclusions are presented in Section V.

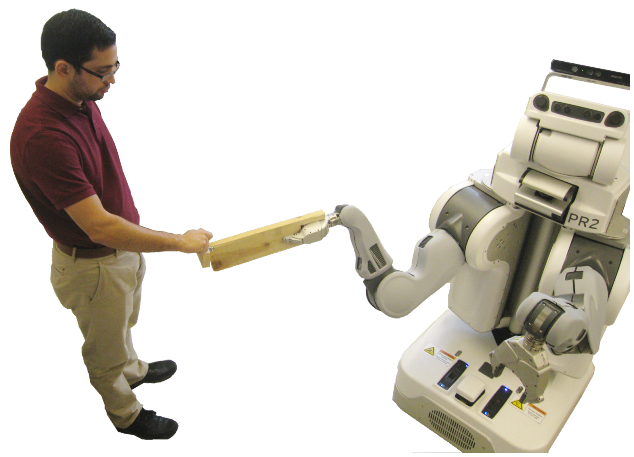

Fig. 1 : Joint manipulation of an object by a robot and a human.

II. RELATED WORK

An important problem for *physical human-robot interaction* (pHRI) is cooperative manipulation of an object jointly held by both a human and a robot. Classically, works in human-robot co-manipulation consider the robot as a passive agent taking care of load compensation and/or stabilization while the human acts as a leader for planning and guiding the cooperative task. A common approach has been to use different types of impedance control with the main goal of improving the safety [1]–[3].

Another issue mentioned in the literature is the number of inputs that the human can exploit in order to control the motion of the object. In a planar setting, for example, the generalized motion of the object can be parameterized by three variables (two for translation and one for orientation). If the human is able to generate both force and torque, the intention for translation can be communicated via applied force, and the intended rotation can be communicated by exerting a torque other than that directly resulting from the applied forces. However, in the case of long objects, the human may not be able to exert torques large enough to be distinguished from noise, and the intention to rotate can

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not be distinguished from the intention to translate via this method [4], [5].

The works that consider this rotation/translation problem can be divided into two main categories. The first includes methods that impose virtual constraints on the robot without considering different modes of motion. In [6], virtual non-holonomic constraints are imposed such that the robot-object system is behaving following the unicycle model. In particular, the forces acting along the line connecting human and robot will translate the robot while forces lying on the orthogonal complement of the line will rotate it. Pump-like constraints are proposed in [7] by considering both virtual translation constraints for the robot's end-effector as well as a reference orientation that should be kept. In [5], the end-effector can only translate while the orientation can change by attaching a passive spherical joint. This method can be implemented through a switching strategy or by using readings of the human torque obtained by a sensor attached at the handle grasped by the human.

The second category consists of methods that consider systems with two different modes that switch from one mode to the other given some switching strategy based on different perception modalities. In [8], voice instruction is used to set operation to translation or rotation mode. Advanced cognitive capabilities such as speech recognition and language understanding are required and thus the speed of the interaction may be significantly reduced. In recent works, proprioception has been used to trigger the switch between different modes of operation: a) Velocity measurements exploited in [9] in order to switch between different type of translation and rotation modes (e.g. turn, walk) with different speed levels b) In [10], the human intention is mainly communicated through haptic and motion input channels.

In this paper, we examine the use of direction and magnitude of applied force to switch between translational and rotational modes, and demonstrate the effect of different switching strategies on the types of motion that can be efficiently commanded.

III. Problem Formulation and Method

In this section we formalize the problem and formulate methods for switching between translational and rotational modes based on direction and magnitude of the applied force.

A. Kinetostatics

We consider a setting in which a human and a robot jointly hold an object. For clarity of presentation in the Figs. 2, 4 we consider a planar setting. The robot is not explicitly aware of the human intention and plan but is equipped with a force/torque sensor attached at its end-effector that provides the robot with force $\mathbf{f}$ and torque $\boldsymbol{\tau}$ measurements. We assume that the human is able to exert only forces, denoted by $\mathbf{f}_h$ to move – rotate or translate – the object. We denote with $\{r\}$ and $\{h\}$ the frames attached at the robot and human grasping points respectively, or the points at which the human and robot can exert forces/torques. The positions of the frames are denoted by $\mathbf{p}_r$, $\mathbf{p}_h$ where the subscript denotes the frame.

Let $\mathbf{s}$ be the vector connecting the origins of the robot and human frames with direction towards $\{h\}$ and define a virtual stick connecting the human and the robot. In our formulation no rotation about $\mathbf{s}$ can be communicated given that human cannot exert torques. The kineto-static formulation of the task is described by the following equations:

$$\begin{aligned} \dot{\mathbf{p}}_r &= \dot{\mathbf{p}}_h + \mathbf{s} \times \boldsymbol{\omega} \\ \mathbf{f} &= \mathbf{f}_h \\ \boldsymbol{\tau} &= \mathbf{s} \times \mathbf{f}_h \end{aligned} \tag{1}$$

where $\dot{\mathbf{p}}_r$ and $\dot{\mathbf{p}}_h$ denote the translational velocity of the robot and the human. We parameterize $\mathbf{f}$ by a scalar positive variable $f = \|\mathbf{f}\|$ and a direction vector $\mathbf{d} = \frac{\mathbf{f}}{\|\mathbf{f}\|}$ and define the unit vector $\boldsymbol{\ell}$ by normalizing $\mathbf{s}$, i.e. $\boldsymbol{\ell} = \frac{\mathbf{s}}{\|\mathbf{s}\|}$.

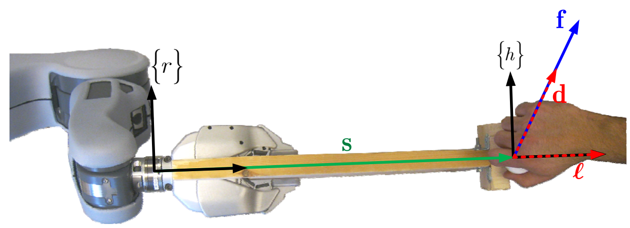


Fig. 2 : Frames are depicted with black arrows, relative position vector $\mathbf{s}$ with green arrow, force $\mathbf{f}$ with blue vector and normalized vectors $\mathbf{d}$ and $\boldsymbol{\ell}$ with dotted red arrows

B. Problem Description and Modes of Operation

We consider a simple admittance controller via velocity control to implement passive robot motions driven by the forces exerted by the human at $\mathbf{p}_h$:

$$\begin{aligned} \dot{\mathbf{p}}_r &= \bar{b}_T \mathbf{f} = \bar{b}_T \mathbf{f}_h \\ \boldsymbol{\omega} &= \bar{b}_R \boldsymbol{\tau} = \bar{b}_R \mathbf{s} \times \mathbf{f}_h \end{aligned} \tag{2}$$

where $\bar{b}_T$ and $\bar{b}_R$ are positive admittance gains inversely affecting the damping of the system. From (2) it is obvious that a human force even if only intended to translate the object also infers a rotation of the object. Translational object motion can also arise even if the human force is always perpendicular to the virtual stick intending only object rotation about the robot end-effector. By appropriately setting the values for the damping coefficients we can define two different mode of operation considered in this work: a) rotation and b) translation mode.

In the *rotation mode* the robot end-effector only allows rotation of the object. This can be achieved by designing the damping controller (2) so that a virtual passive spherical joint is created at $\mathbf{p}_r$, by considering low values for the admittance parameters related to the translational motion i.e. $\bar{b}_T = 0$. The rotational motion of the object is affected by the forces exerted by the human. The internal forces in this case lie along the axis $\boldsymbol{\ell}$.

In the *translation mode* the object can be freely translated by the human. This behavior can be achieved by considering low values for the admittance parameters related to the rotational motion or $\bar{b}_R = 0$.

C. Switching Conditions for Mode Selection

In this section we propose different switching conditions between the two modes of operation to enable the human to communicate the intention for translation or rotation via haptic feedback.

First we specify a force threshold $f_{\min}$ for motion; when the magnitude of the force is less than the threshold the end-effector cannot be translated or rotated. This threshold can typically be set slightly above the measurement noise to avoid unintended motion of the object due to noisy force signals. Hence the controller can be formally described as follows:

$$\begin{aligned} \dot{\mathbf{p}}_r &= \begin{cases} \sigma \bar{b}_T \mathbf{f}, & \|\mathbf{f}\| \geq f_{\min} \\ 0, & \|\mathbf{f}\| < f_{\min} \end{cases} \\ \boldsymbol{\omega} &= \begin{cases} (1-\sigma)\, \bar{b}_R \boldsymbol{\tau}, & \|\mathbf{f}\| \geq f_{\min} \\ 0, & \|\mathbf{f}\| < f_{\min} \end{cases} \end{aligned} \tag{3}$$

where $\sigma(\cdot) \in [0,1]$ is defined based on the following switching conditions.

1) Switching based on the force direction: The first condition is based on the angle θ formed between the human force direction $\mathbf{d}$ and the virtual stick direction $\boldsymbol{\ell}$. In particular we consider a double cone with main axis $\boldsymbol{\ell}$, apex at the origin of $\{h\}$ and aperture $2\theta_0$, with θ_0 being a threshold for the angle θ. If the forces lies inside the cone, the robot operates in the translation mode and if the force lies outside the cone the robot operates in the rotation mode. To clarify this condition we consider an example (see Fig. 4) of a human that wants to translate the object perpendicular to the direction of the virtual stick at $t = 0$ and hence exerts forces with constant direction. Initially the object is rotating about the robot end-effector and as the orientation of the virtual stick changes in the world frame, angle θ decreases from 90 deg to θ_0 and the translation mode is activated. From this example we see that if the human wants to avoid unintended rotation, θ_0 should be chosen close to 90 deg. On the other hand choosing θ_0 close to 90 deg makes it difficult to rotate the object since chattering arises due to the narrow angle zone and human inaccuracy. This switching function is depicted in Fig. 5i and is formally described using a sign function as follows:

$$\sigma(\chi) = \frac{1}{2}\left[1 - \operatorname{sgn}(\chi)\right] \tag{4}$$

with:

$$\chi \triangleq \operatorname{acos}|\boldsymbol{\ell}^\top \mathbf{d}| - \theta_0 \tag{5}$$

where $\operatorname{acos}|\boldsymbol{\ell}^\top \mathbf{d}|$ is the angle with cosine $|\boldsymbol{\ell}^\top \mathbf{d}|$ and θ_0 take values between 0 and 90 deg. Alternatively we can represent it as a state machine depicted in Fig. 3 with the conditions for switching between modes given by:

$$\begin{aligned} C_T &\equiv (\operatorname{acos}|\boldsymbol{\ell}^\top \mathbf{d}| < \theta_0) \\ C_R &\equiv (\operatorname{acos}|\boldsymbol{\ell}^\top \mathbf{d}| > \theta_0) \end{aligned} \tag{6}$$

To avoid switchings due to force measurement noise we can also implement the switching function as a relay with hysteresis as shown in Fig. 5ii. Notice that in this case the switching threshold from translation to rotation i.e θ_0

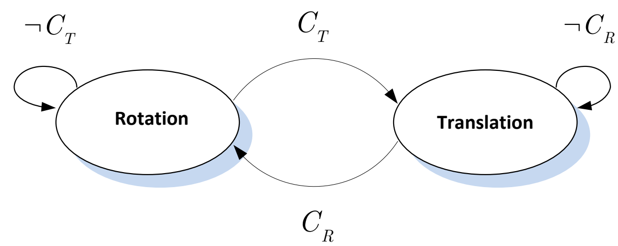


Fig. 3 : A simple state machine: The two mode of operations. When the switching conditions C_T is satisfied then a transition from rotation to translation mode is triggered otherwise the system operates in the rotation mode. When the switching conditions C_R is satisfied then a transition from translation to rotation mode is triggered otherwise the system operates in the translation mode.

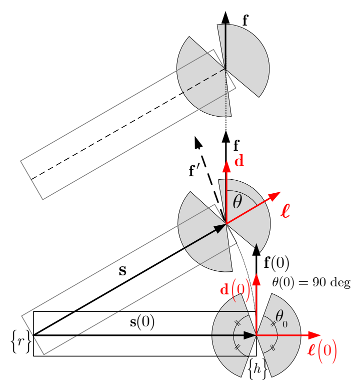


Fig. 4 : In the rotation mode the forces exerted by the human can only rotate the object about the robot end-effector. At the initial configuration the force exerted by the human is perpendicular to the axis $\boldsymbol{\ell}$ i.e. $\theta = 90^\circ > \theta_0$. For a force $\mathbf{f}'$, $\theta > \theta_0$ the object will continue to rotate. However, when $\mathbf{f}$ enters the gray-filled double cone the system switches to the translation mode and the object will be translated along the line of the exerted force.

is decreased by a constant δ_θ when the system switches from rotation to translation, i.e. the state machine of Fig. 3 incorporates the following conditions:

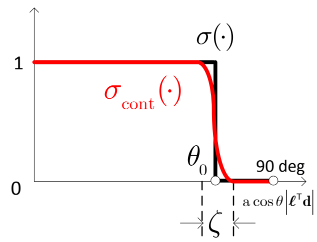
$$\begin{aligned} C_T &\equiv (\operatorname{acos}|\boldsymbol{\ell}^\top \mathbf{d}| < \theta_0 - \delta_\theta) \\ C_R &\equiv (\operatorname{acos}|\boldsymbol{\ell}^\top \mathbf{d}| > \theta_0) \end{aligned} \tag{7}$$

In this case chattering is expected to be reduced but it is still difficult for the human user to enter the rotation mode if the angle threshold is close to 90 deg.

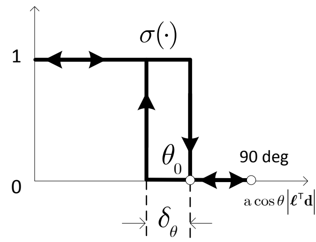
Another way to avoid chattering is to apply a smooth transition between the two modes by considering a continuous version of σ where the sharp transition is replaced by a smoother one with duration ζ (Fig. 5i):

$$\sigma_{\text{cont}}(\chi) = \begin{cases} \sigma(\chi), & \operatorname{acos}|\boldsymbol{\ell}^\top \mathbf{d}| \notin [\theta_0 - \frac{\zeta}{2}, \theta_0 + \frac{\zeta}{2}] \\ \frac{1}{2}[1 - \sin(\frac{\pi}{\zeta}\chi)] & \operatorname{acos}|\boldsymbol{\ell}^\top \mathbf{d}| \in [\theta_0 - \frac{\zeta}{2}, \theta_0 + \frac{\zeta}{2}] \end{cases} \tag{8}$$

Without discrete states, the state machine representation is not relevant. In our discussion example the rotation angle before entering the intended translation mode increases. This



(i) Discrete (black) and Continuous (red)



(ii) Relay with hysteresis

Fig. 5 : Switching functions based on angle θ formed between $\mathbf{d}$ and $\boldsymbol{\ell}$

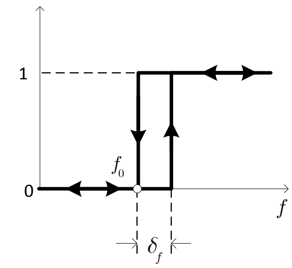


Fig. 6 : Switching functions with Hysteresis based on the force magnitude

requires extra effort for the human to correct the orientation error at the end. Hence, there is a trade-off between smooth operation and accurate mapping of the human intention to the robot trajectory. For the extreme case $\sigma = 1/2$ – which corresponds to $\zeta \rightarrow \infty$ – the continuous version can be considered as a damping controller which cannot distinguish between rotation and translation, as in (2).

2) Switching based on the force magnitude: This switching condition based on force magnitude is motivated by the following observations:

1) When the human tries to command translation while in rotation mode, internal forces will arise along the virtual stick direction. The admittance controller compensates for the motive force perpendicular to the virtual stick but it cannot compensate for the force component along the virtual stick direction. In the translation mode force compensation is achieved in all possible directions.
2) There is a proportional relation between the forces exerted by the human and the velocity of the robot end-effector tuned by the gains $\bar{b}_T$ and $\bar{b}_R$.

Hence we can set a force magnitude threshold f_0 and link the rotation mode to forces (velocities) lower than this threshold. To avoid unintended switching chattering due to inaccurate operation or noisy measurements the switching condition is defined as a relay with hysterisis δ_f (Fig. 6) as follows:

$$\begin{aligned} C_T &\equiv (f > f_0 + \delta_f) \\ C_R &\equiv (f < f_0) \end{aligned} \tag{9}$$

The intuition behind this condition is that the human must reduce speed (forces) to allow a switch to rotation mode, while effort (force) is needed to switch to translation mode.

IV. Experiments

The proposed methods were implemented on a robot, and examined in a proof-of-concept type study.

A. Experimental Setup and Scenario

To demonstrate the performance of the different approaches, we implemented them on a PR2 robot from Willow Garage. Our PR2 robot is approximately human sized, with two arms with 7 DoF each. Each arm is equipped with an ATI mini 45 force/torque sensor at the wrist, and a parallel gripper. Velocity control is possible at 1000 Hz, but the robot is compliant and large external force will cause some motion of the joints. More details on the PR2 can be found in [11].

We implemented the following prototype control systems:

- **System A** uses non-hysteresis switching based on force direction, with switching conditions defined as in (6), with $\theta_0 = 75$ deg, i.e. rotational mode is engaged for force applied at angles less than 15 deg from the tangential direction, and translational mode is engaged for angles greater than 15 deg from the tangential direction.
- **System B** uses hysteresis-type switching based on force direction, with switching conditions defined as in (7), with $\theta_0 = 82$ deg, and $\delta_\theta = 12$ deg. i.e. rotational mode is engaged for force angles less than 8 deg from the tangential direction, and translational mode is engaged for force angles greater than 20 deg from the tangential.
- **System C** uses a continuous switching condition, with σ defined as in (8), with $\theta_0 = 75$ deg, and $\zeta = 5$ deg, i.e. rotational mode is engaged when force angles less than 10 deg from the tangential direction, and translational mode is engaged for force angles greater than 20 deg from the tangential, with a continuous transition between these two values.
- **System D** uses hysteresis-type switching based on force magnitude, with conditions as defined in (9), with $f_0 =$ 0.3 N, and $\delta_f = 3.2$ N, i.e, rotational mode is engaged when forces fall below 0.3 N, and translational mode when forces rise above 3.5 N.

Values were found empirically, chosen to give a balanced performance for both rotational and translational modes. Appropriate values may vary between setups, but in general, significantly changing the thresholds will make either mode become more dominant and the other more difficult to engage and/or keep. All prototype systems use the admittance controllers in (3), with the admittance gains set to $\bar{b}_T =$ 0.08m/(sN) and $\bar{b}_R = 0.3$ rad/(sNm).

For the experiment, we let a human subject and the robot each grasp one end of a wooden board, of 0.3 m length. The human grasps the board by a freely rotating handle, thus only allowing the application of forces at the interaction point, not torque. The setup is illustrated in Fig. 7.

For each approach **A–D**, we demonstrate the performance of three different tasks:

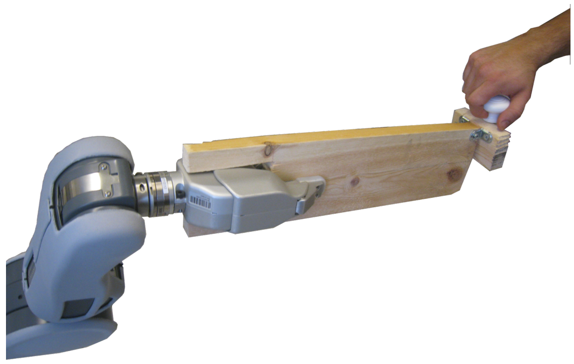
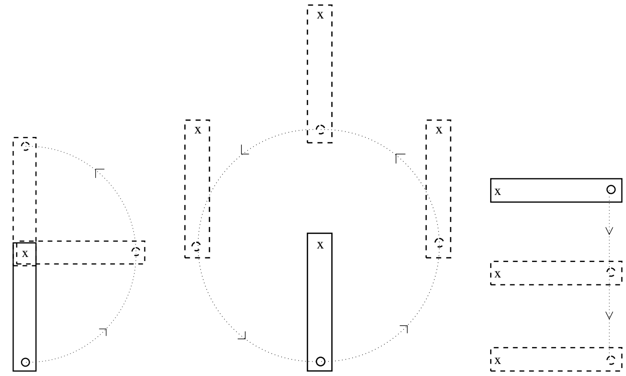


Fig. 7 : The experiments were carried out with a 30 cm long wooden object. The human holds a freely rotating handle, and is not able to transfer any torque directly to the object.



(i) Task 1. Rotation (ii) Task 2. Circular motion. (iii) Task 3. Linear motion.

Fig. 8 : The three tasks used in the experiment. The human grasping point is marked with an "o", and the robot grasping point is marked with an "x".

1) **Circular rotational motion.** Here, the human tries to rotate the object about the point grasped by the robot, without translation, see Fig. 8i. The object is initially at rest, in the robot starts in rotational mode. The performance of this task will be measured by the amount of mode switching between translational and rotational modes, and the amount of unwanted translation of the object. Both these should be as low as possible, ideally zero.
2) **Circular translational motion.** Here, the human tries to move the object around a circular trajectory without rotation, see Fig. 8ii. The object is initially in motion, with the robot in translational mode. The performance of this task will be measured by the amount of mode switching between translational and rotational modes, and the amount of unwanted rotation of the object. Both these should be as low as possible, ideally zero.
3) **Straight line translational motion.** Here, the human tries to move the object along a straight line perpendicular to ℓ, without rotation, see Fig. 8iii. The object is initially at rest, and the robot starts in rotational mode, so that the human input is initially indistinguishable from a commanded rotational motion. The performance of this task will be measured by the amount of mode switching between translational and rotational modes, and the amount of unwanted rotation of the object. Both these should be as low as possible, ideally with zero rotation and just a single mode switch from rotational to translational mode.

For System **C**, with continuous modes, the amount of mode switching is measured as the number of time that σ passes the value 0.5. All rotations are measured as the rotation of the robot end-effector, which is fixed to the object, and all translations are measured as translations of the end-effector, as this is designed to be the center of rotation. For each combination of task and system, four trials were performed. The variation between trials of the same setup were not significant for the following discussion.

B. Experimental Results

Here we present and discuss the results from the experiments, divided by task.

1) Task 1 - Rotation: For this task, the measured metrics were the total amount of translation, and the number of mode switches. The average result over 4 tries is presented in Table I, and typical motion trajectories are presented in Fig. 9.

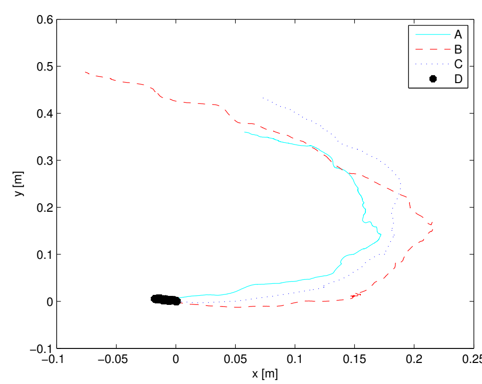


Fig. 9 : Task 1, state space. The plots show the trajectories of the point grasped by the robot.

In this experiment, it is clear that the systems based on the direction of force, i.e. systems **A**, **B**, and **C**, have severe problems with chattering as mode switching occurs several hundred times for a simple semicircular motion.

TABLE I : Performance metrics for Task 1, object rotation. The small translational movement for D is caused by the arm compliance.

system	transl [m]	num. mode switch
A	0.404	910
B	0.579	844
C	0.477	356
D	0.020	0

TABLE II : Performance metrics for Task 2, circular translation. Note that rotational stiffness is higher, so compliance does not result in significant rotation.

system	rot [deg]	num. mode switch
A	28.6	38
B	28.8	28
C	17.6	20
D	0.0	0

This chattering is very obvious to the user. Also, each time spent in translational mode results in a small translation, which adds up to significant motion over the duration of the task. The system based on force magnitude, i.e. system **D**, performs significantly better, with no mode switches over several tries, and hence no translation due to entering the translational mode. The small translation originates from the position tracking error of the inherently compliant robot.

The poor performance of the systems based on force direction can be explained by the design of the admittance controller. The force component in the tangential direction of rotation is canceled out by the rotational admittance controller, while the force component (mostly noise) in the radial direction is left. Thus, the direction of the resulting force has a very high noise content, and switching is engaged at high frequencies. The noise is too high for the hysteresis of System **B** to have any major positive effect. The continuous mode of System **C** removes some higher frequencies of the chattering, making the operation smoother, but otherwise not significantly improved.

2) Task 2 - Circular Translation: For this task, the measured metrics were the total amount of rotation, and the number of mode switches. The average results over the 4 tries are presented in Table II, and typical motion trajectories are presented in Fig. 10, while the angle of rotation is shown in Fig. 11.

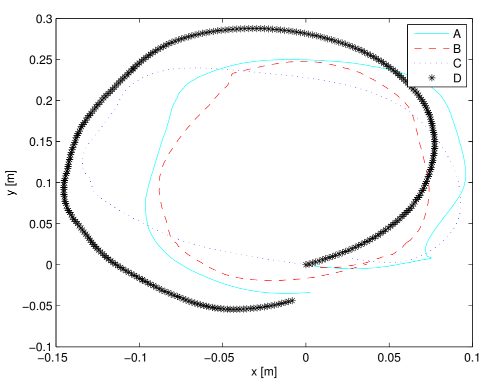


Fig. 10 : Task 2, position state space.

As for the previous task, there is still some spurious mode switching for the systems based on force direction (**A**, **B**, and **C**). This mainly occurs when the object is moved perpendicular to ℓ, twice per lap. When this happens, the object is rotated slightly, until it goes back to translational mode. When in translational mode, chattering is smaller,

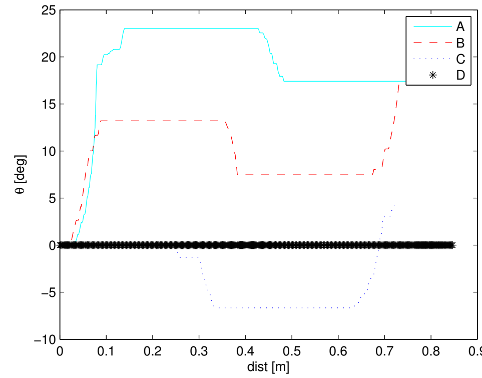


Fig. 11 : Task 2, angles, function of motion distance.

TABLE III : Performance metrics for Task 3, linear translation. Note that system D have one task switch, after some small initial rotation. system A shows excessive chattering, B and C slightly less.

system	rot [deg]	num. mode switch
A	38.2	113
B	26.2	49
C	27.8	29
D	4.3	1

as there is less noise in the direction of applied force in translational mode, as the translational admittance controller lowers the applied forces equally in all directions.

For the system based on force magnitude, no switching occurs as long as the velocity (and hence the force) is high enough to not enter rotational mode.

3) Task 3 - Linear Translation: For this task, the measured metrics were the total amount of rotation, and the number of mode switches. The average results over the 4 tries are presented in Table III, and typical motion trajectories are presented in Fig. 12, while the angle of rotation is shown in Fig. 13. Note that even though the human moves the object handle in a straight line, the rotation of the object forces the robot end-effector trajectory closer to the human trajectory, and the motion trajectories for systems with high levels of rotation tend to deviate to the left in Fig. 12.

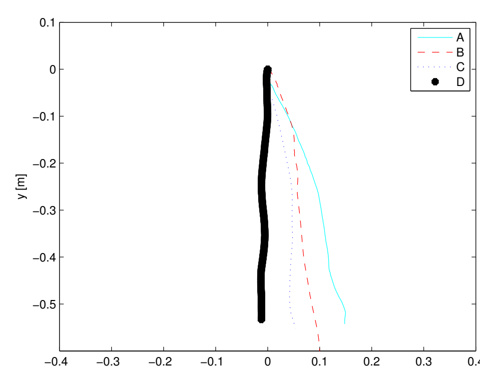


Fig. 12 : Task 3, position state space.

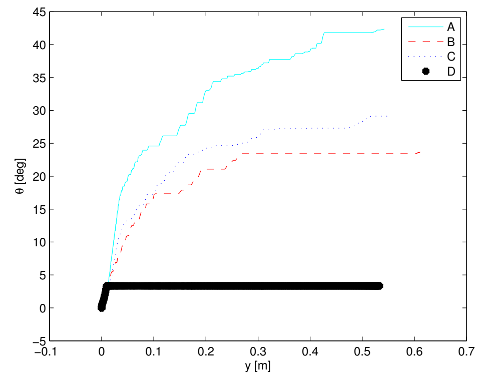


Fig. 13 : Task 3, angles as function of motion distance in y direction.

As in Task 1, there is significant mode switching in the initial phase for the systems based on force direction, for similar reasons. When the object has finally rotated enough so that the direction of motion is outside the limits defined for the rotational mode, the hysteresis of System **B** keeps the robot in translational mode significantly better than System **A**, and the continuous mode of System **C** lowers the amount of high-frequency chattering, also adding to the stability of the behavior. Both systems **A** and **B** rotate slightly more than the expected 15 degrees of the switching limit before settling in translational mode, this is mostly due to noise sensitivity.

As for Task 2, System **D**, based on force magnitude stays robustly in translational mode once entered, and the initial rotation is much smaller than for any of the systems based on force direction.

C. *Observations and Comments*

As the human input was not exactly the same for all tries, and only one subject was used, the numerical results should be seen as qualitative indicators, not quantitative. It is still clear that the performance is substantially improved when force magnitude is used as the switching criterion. The subjective experience of the subject also supports this.

For all modes of operation demonstrated here, System **D** performs as desired, but there are two conditions not demonstrated here that will cause this System to fail. The first is when very fast rotation is desired. Given our controller parameters, rotational velocities above $0.315\ \mathrm{rad/s}$ will require forces of a magnitude above the switching threshold, and translational mode will be engaged. Similarly, when slow translation is desired, translational velocities below $0.024\ \mathrm{m/s}$, will result in chattering, as forces below the switching threshold are required. These thresholds can be moved, at the expense of other performance metrics, but the behavior itself can not be completely removed.

V. Conclusions

In this paper we have demonstrated how to use force measurements to trigger switching conditions for a dual mode controller to address the rotation/translation problem for human robot collaborative manipulation. We show that using force magnitude as an indicator of the humans intention performs substantially better than using force direction. The cause for this is found in the admittance controllers used. An admittance controller for rotation will inherently cause noisy measurements of force direction. Also, the intention to perform translation will typically generate much higher forces on the object than the desire to rotate it, given the admittance controllers.

For future work, we identify two major issues of study. The first is to evaluate the performance of the proposed controller for a real manipulation task, in a rigorous user study. The second is to find a way to treat very fast rotations and very slow translations. This will require more advanced means to identify user intention,

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