Measuring Intent in Human-Robot Cooperative Manipulation

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Abstract—**To effectively interact with people in a physically assistive role, robots will need to be able to cooperatively manipulate objects with a human partner. For example, it can be very difficult for an individual to manipulate a long or heavy object. An assistant can help to share the load, and improve the maneuverability of the object. Each partner can communicate objectives (*e.g.*, move around an obstacle or put the object down) via non-verbal cues (*e.g.*, moving the end of the object in a particular direction, changing speed, or tugging).**

Herein, non-verbal communication in a human-robot coordinated manipulation task is addressed using a small articulated robot arm equipped with a 6-axis wrist mounted force/torque sensor and joint angle encoders. The robot controller uses a Jacobian Transpose velocity PD control scheme with gravity compensation. To aid collaborative manipulation we implement a uniform impedance controller at the robot end-effector with an attractive force to a virtual path in the style of a cobot. Unlike a cobot, this path is recomputed online as a function of user input. In our present research, we utilize force/torque sensor measurements to identify intentional user communications specifying a change in the task direction. We consider the impact of path recomputation and the resulting robot haptic feedback on user physiological response.

I. Introduction

Robots have been successfully employed in industrial settings to improve productivity and perform dangerous or monotonous tasks. Traditionally, robots have been kept in closed work-cells, avoiding interaction with humans. This practice has relegated robots to limiting roles. More recently, however, attention has turned to the use of robots to aid humans both on the factory floor and in homes and offices. An important step towards this goal is the acquisition, analysis, and integration of both explicit and non-explicit user communications within the human-robot control loop, such as user intent. Essentially, the robot should respond to non-verbal cues, similar to the "body language" of the user. Through the incorporation of non explicit communication, we hope that human-robot cooperation can be improved.

In our recent work, non-explicit control inputs from the human user have been integrated into the robot control system in order to provide robot motions that are perceived to be more comfortable and safe by the user. The orientation of a user's face, the position of their body, and physiological cues such as heart rate, skin conductance, etc. were tracked in [7]. However, in manipulation activities, applied force/torque also is an important signal for measuring intent. In [18], a coordinated manipulation scenario was investigated in which a load was carried between a human and a robot. The robot was a 6-DOF (degree-of-freedom) anthropomorphic manipulator with a 6-axis force/torque sensor at the end effector. A virtual nonholonomic constraint was achieved through the use of an impedance based control law using the output of the 6-axis sensor. Constraining a manipulator nonholonomically such that its behavior resembles that of something familiar to the user can make a manipulation task more intuitive [16]. Both of the aforementioned papers did not consider user intent; they could be identified as passive control strategies.

Control schemes based on user intent for vehicle guidance, such as [8] and [10] have also been reported. In both papers, a pre-planned path was used. User intent was interpreted from a 6-axis force/torque sensor and realtime path modifications were imposed based on the component of the force orthogonal to the planned trajectory. In the former paper, a potential-field-based control scheme was adopted and modification of the path was performed when the magnitude of the orthogonal force exceeded a limit for a specified period of time. In the latter paper, a scaling factor, dependent on the orthogonal force and the distance to the path, was included to introduce elasticity into the path controller.

The main focus of this work is an investigation of a force based control scheme for communicating user intent in a cooperative manipulation task between a human and a 6-DOF articulated robot. Furthermore, unlike many previous works, we do not assume that the path along which the load will be moved is known *a priori*. We also utilize previous work in biometrically measured affect to corroborate the force-based user intent measures developed here.

It is important that robots physically interacting with humans take into account the intentions of their human partners [10]. Without some measure of intent, a robot would be unable to discern unintentional forces/torques applied to the load by a human (or another robot, for that matter) from those that were intended. While this might only lead to less stable cooperative behaviors in the general case, one can consider what would happen should the human become distracted from the task. The forces and torques along unconstrained axes would not

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be opposed, and thus a significant unintended displacement of the load might be *facilitated* by the robot.

In Section II, we propose a synthesis of the contributions of Long et al. [8] and Takubo et al. [18] with an innovative extension to capture user intent. The force input to our isotropic impedance controller guides the user along a planned path. If the user indicates through a force input that an alternate path should be followed, the robot will adopt the new path and the attractive force guidance is recomputed.

In Section III we consider closing the communication loop between the user and the robot. In this work, as a by-product of the adoption of the new path, the user receives a haptic cue, which is confirmed by a measurable physiological response. We hypothesize that this *orienting response* can be used as an implicit acknowledgment by the user of the robot's response. Finally, in Section IV we describe our experimental setup, and present preliminary experimental results.

II. Guided Control Scheme

In a cooperative load-sharing task, the robot controller should be compliant with operator input. Therefore, we begin with an impedance-based approach. In so doing, a desired inertia/friction are presented at the end effector by specifying these physical parameters directly in the robot controller. We begin with the structure of [18]. The desired end-effector position and orientation in Cartesian space is related to the forces/torques measured at the robot's end effector as follows:

$$\begin{aligned} f_{Xr} &= m_X \ddot{e}_{Xr} + b_X \dot{e}_{Xr} \\ f_{Yr} &= m_Y \ddot{e}_{Yr} + b_Y \dot{e}_{Yr} \\ f_{Zr} &= m_Z \ddot{e}_{Zr} + b_Z \dot{e}_{Zr} \\ \tau_{Xr} &= I_X \ddot{\theta}_{Xr} + c_X \dot{\theta}_{Xr} \\ \tau_{Yr} &= I_Y \ddot{\theta}_{Yr} + c_Y \dot{\theta}_{Yr} \\ \tau_{Zr} &= I_Z \ddot{\theta}_{Zr} + c_Z \dot{\theta}_{Zr}, \end{aligned} \tag{1}$$

where $(f_{Xr}, f_{Yr}, f_{Zr}, \tau_{Xr}, \tau_{Yr}, \tau_{Zr})$ are forces/torques obtained from a 6-axis sensor mounted at the end effector, $(\dot{e}_{Xr}, \dot{e}_{Yr}, \dot{e}_{Zr})$ and $(\dot{\theta}_{Xr}, \dot{\theta}_{Yr}, \dot{\theta}_{Zr})$ are linear and angular velocities of the robot end effector frame, and $(\ddot{e}_{Xr}, \ddot{e}_{Xr}, \ddot{e}_{Xr})$ and $(\ddot{\theta}_{Xr}, \ddot{\theta}_{Yr}, \ddot{\theta}_{Zr})$ are the acceleration and angular acceleration vectors. Finally, $(m_X, m_Y, m_Z, I_X, I_Y, I_Z)$ and $(b_X, b_Y, b_Z, c_X, c_Y, c_Z)$ are the inertial and friction coefficients that define the impedance control law. In [18], these coefficients were specified so as to make the impedance controller anisotropic, opposing motion along specific axes more than others. However, in this work, equal inertial and frictional coefficients were used for each axis, producing in an isotropic impedance constraint.

Forces/torques are applied by the user to the robot's end effector through a load, illustrated by Figure 1. The end effector's approach vector is aligned with the long axis of the load. The inertia/friction for the orientation of the end effector are minimal, resulting in an arm behaviour that is fully compliant with user force/torque inputs applied through the load.

By rearranging (1) and integrating once, the velocity of the end effector that should result from user input is obtained.

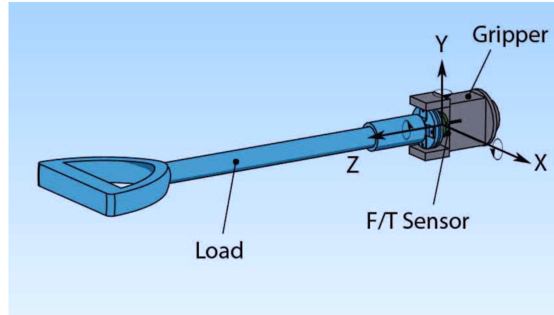

Fig. 1. A proposed load is shown with the robot's end effector frame labeled. A servo gripper has been included in this figure to illustrate the approach vector (z-axis) relative to both the end-effector and the load.

Thus, following [17], a Cartesian space control is considered to be the most appropriate for controlling interactions between the manipulator and the environment. In particular, as shown in Figure 2, we adopt a Cartesian space PD controller with gravity compensation [5]. Unlike the conventional approach in [17], we servo on velocity, not position. In doing so, we avoid the need to doubly integrate the somewhat noisy output from the force/torque sensor to generate commands for the PD controller, resulting in a smoother overall response to user input. This also is the approach taken by Takubo et al. [18]. However, a Jacobian-transpose control scheme still can be employed, as velocity is tangential to displacement, and thus the direction of the resulting control signal $\mathbf{u}$ is the same in both cases. The equation that governs the control loop is:

$$\mathbf{u} = \mathbf{g}(\mathbf{q}) + J_n^T(\mathbf{q})[K_P \dot{\mathbf{p}}_{error} + K_D \ddot{\mathbf{p}}_{error}], \tag{2}$$

where $\dot{\mathbf{p}}_{error}$ is the end effector velocity command output from the impedance constraint, $\dot{\mathbf{p}}_{cmd}$, and the actual end effector velocity, $\dot{\mathbf{p}}_e$. $\mathbf{g}(\mathbf{q})$ performs a nonlinear compensation of joint space gravitational forces and $J_n^T(\mathbf{q})$ is the transpose of the Jacobian in the frame of the end effector given $\mathbf{q}$, the pose of the robot in configuration space.

A. User Intent Based Control Scheme

Our full robot controller assists the user manipulating the load along a virtual path in Cartesian space that is recomputed in response to user input. In this section we describe this controller and the manner in which user intent is incorporated into the overall control system. Our proposed controller is presented in Figure 3.

Paths in this study take the form of straight lines represented by both a point in space, $\mathbf{p}_{path}$, and a unit vector, $\mathbf{v}_{path}$, that indicates the path's direction. The force input to the impedance constraint is the sum of the user-applied force and an elastic force towards the path, computed as

$$\mathbf{F}_{path} = K_s \left[\mathbf{p}_{path} + [(\mathbf{p}_e - \mathbf{p}_{path}) \cdot \mathbf{v}_{path}] \mathbf{v}_{path} - \mathbf{p}_e) \right], \tag{3}$$

where K_s is a spring constant relating the magnitude of the elastic force to the distance between the end effector and the path, and $\mathbf{p}_e$ is the position of the end effector. Note that we only modify the force component of the 6-axis signal; torques

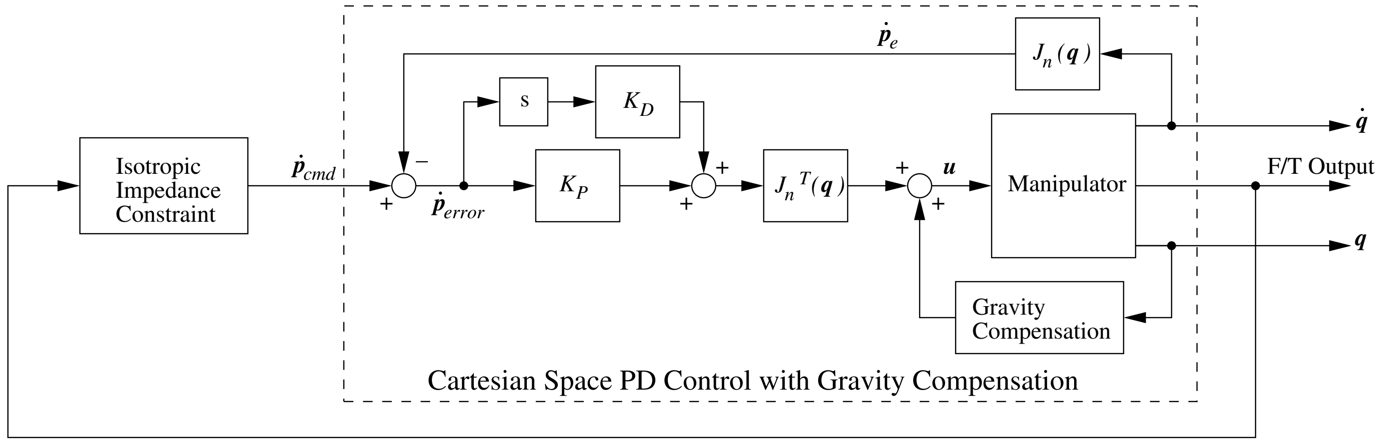

Fig. 2. Our controller for cooperative human-robot load manipulation is structured around a Cartesian space PD plus G velocity controller. Forces/torques applied to the 6-axis load cell at the robot's end effector are converted into a velocity command by the impedance constraint, and the velocity of the end effector tracks this command.

are passed to the impedance constraint unperturbed. Thus the user can manipulate the load along the path unopposed as well its orientation, but the load will be kept near to the path via $\mathbf{F}_{path}$ in a manner similar to the controller described in [8]. In that work, however, the virtual path was static. Using our controller, the user can induce the robot to adopt a new path by pushing the load sufficiently far off of the current path such that the magnitude of $\mathbf{F}_{path}$ exceeds F_{max}. When this occurs, a new path is computed using the end effector's current position for $\mathbf{p}_{path}$ and the direction of its z-axis for $\mathbf{v}_{path}$.

III. User Intent Monitoring Based on Biometrics Measures

Physiological monitoring systems have been well documented and proven useful to extract information about users' attention, stress level, and affective states, both for human-computer and human-robot interaction [11]–[15]. Signals proposed for use in human-computer interfaces include skin conductance, heart rate, pupil dilation and neural and muscle activity. Rani et al. [13], [14] used heart rate analysis and multiple physiological signals to estimate human stress levels during video game playing. Kulić and Croft [7] used Hidden Markov Models to estimate affective state response to articulated robot motions. Picard et al. [12], and Kim et al. [4] used Support Vector Machines to estimate user affective state for human-computer interaction. In [2] biosignal activities and eye movements were used to infer users' preferences on a two-alternative, forced-choice task.

Our study takes advantage of the orienting response, an involuntary physiological response to a stimulus. A person's orienting response is accompanied by a variety of well-documented physiological changes such as increased electromyogram activity, increase in amplitude and decrease in frequency of respiration, a slowing of heart rate, an increase in blood volume, and changes in electrodermal activity (skin conductance) [1]. Orienting responses are commonly observed at each introduction of a novel stimulus, but are subject to habituation.

Immediately prior to the adoption of a new virtual path, the robot will exert a force of F_{max} on the user. Regardless of the particular path adopted, the new path will pass through the end effector's current position at the time of adoption, and thus $\mathbf{F}_{path}$ will immediately drop to zero. This sudden change in force will be apparent to the user. We hypothesize that this haptic stimulus associated with the robot's adoption of a new path will generate an orienting response. We propose to take advantage of this measured response in order to confirm the user's recognition that the path has changed. We believe that this cue can be used to confirm whether the user is attending to the task. The lack of an orienting response could suggest that the user's attention is elsewhere, and the robot therefore may need to provide a higher level of task guidance, or act to reacquire the user's attention before allowing the task to proceed. In this way, biosignals may provide an additional mechanism to confirm user's intent estimated from the force/torque signal.

For this work we utilize a fuzzy logic based engine [6] to identify the orienting response at the onset of a change in arousal that is estimated based on heart rate, skin conductance, and tricept muscle activity.

IV. Experimental Setup

Our experimental setup comprises a CRS A460 arm, which is anthropomorphic and human-sized, with a maximum payload of 2kg. At the gripper of the arm we have attached an ATI Mini45 SI-290-10 force/torque sensor and a shovel handle for user interaction. A photograph of a cooperative manipulation trial is given in Figure 4. The value K_s was 300 N/m, and F_{max} was set to 25 N. The motor electrical constants used in the low level control were identified using the methods described in [3].

The ProComp Infinity system from Thought Technology [9] was used to gather the physiological data used in this study. This system has been used for several physiological studies in human-robot and human-computer interaction [12]–[14], and

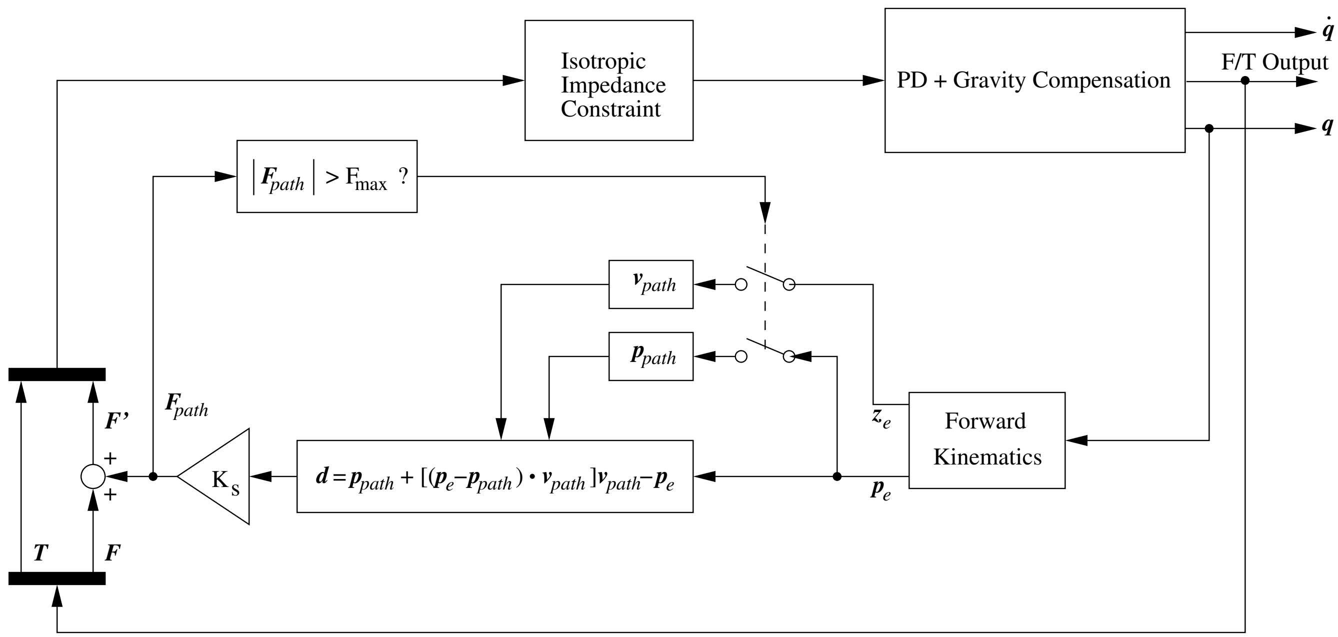

Fig. 3. Our user intent based control scheme builds upon the isotropic impedance controller shown in Figure 2 by adding an an attractive force back to a virtual path in Cartesian space that is proportional to the end effector's distance from the path. By pushing the load sufficiently far from the path, a user indicates to the robot that a new path should be adopted, which is specified by the current position and heading of the robot end effector at the time of recomputation.

is used by therapists for biofeedback applications [9]. Heart muscle activity, skin conductance , and tricept muscle activity on the dominant arm were measured. The heart muscle activity was measured via electrocardiogram (ECG) measurement using EKG Flex/Pro sensor. Skin conductance was measured using the SCFlex-Pro sensor. Tricept muscle activity was measured with the Myoscan Pro Electromyography (EMG) sensor. All biometric sensor data was collected at 256 Hz. This rate is sufficient for capturing physiological signal events. The acquisition of robot controller data and physiological data computer was synchronized at the beginning of each trial.

In our pilot study, at the onset of interaction, the guide path used by the robot is set to be orthogonal to the path along which the user is instructed to manipulate the load (see Figure 5). As the user moves the load, the force exerted by the robot to push the load back to the path increases with the distance to the path as with typical cobotic guidance. Once the attractive force back to the path reaches F_{max}, the robot responds by recomputing a path that is aligned with the current user motion. The immediate result of the recomputation is a haptic "release", similar to stiction behaviour, as the robot adopts the user's new path.

As shown in Figure 6, the user arousal as estimated by our fuzzy logic engine is relatively constant as the load is pushed further from the initial virtual path (the distance to the path can be inferred from the rise in the force applied to the load). As the force drops following path recomputation, arousal dips and then quickly rises 2-3 seconds later. This rise in arousal measure, typical of an orienting response, suggests that the user indeed responded to the haptic stimulus resulting from the change in virtual path.

V. Conclusion

In this work, we have proposed a new robot controller for cooperative load manipulation by a human and a robot. This controller builds upon those reported in previous works by

Fig. 4. This figure illustrates how the user and the robot interact through a shared load. The user manipulates one end of a long, slender load, which is connected to the robot's end effector by a 6-axis force/torque sensor. The robot used is a CRS A460 6-DOF articulated arm.

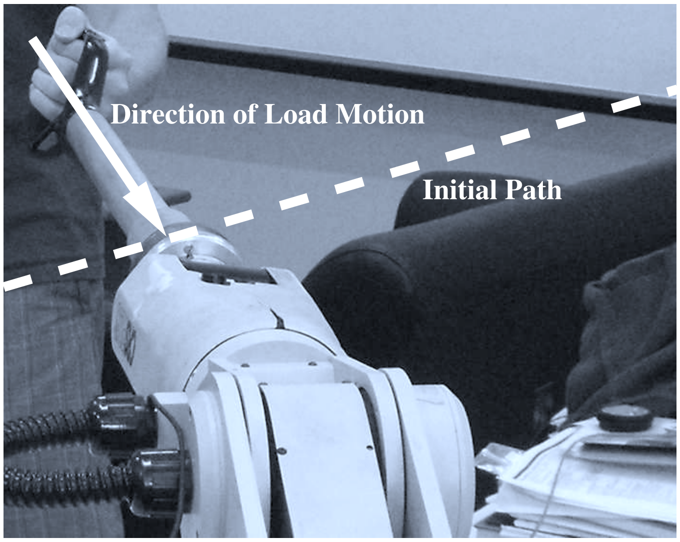

Fig. 5. At the beginning of each trial, the initial virtual path is orthogonal to the direction along which the load is manipulated. When instructed to do so, the user pushes the load forward until the robot computes a new path in response. Through a variety of biometric sensors on the user, the user's physiological response to the haptic feedback resulting from path recomputation is assessed.

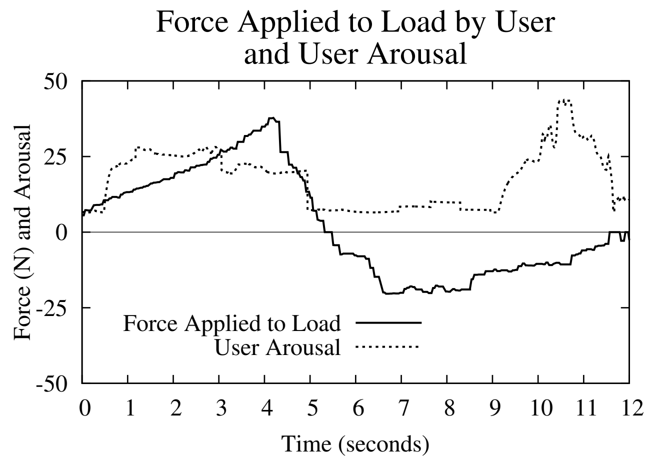

Fig. 6. In this figure, the force applied on the load by the user is plotted along with user arousal as computed by our fuzzy-logic engine over the course of an experimental trial. As the load is pushed further from the path, the force opposing the operator builds. Eventually, it exceeds F_{max} and a new path is recomputed, causing $\mathbf{F}_{path}$ to drop to zero. This sudden change in force elicits a change in the operator's arousal. The rise in arousal a few seconds after the adoption of the new path is typical of an *orienting response*, indicating that at some level the operator was attending to the robot.

employing a virtual guide path for the load that is recomputed by the robot as a function of user input. The manner in which one path is replaced with another presents a haptic stimulus to the user in the form of sudden reduction in the force with which the robot opposes load displacement. In this limited pilot study, we demonstrated that this stimulus can elicit an orienting response from the user, detectable via biometric data measured from the user during an interaction trial.

We concede that the results while promising are very preliminary (very limited testing). However, we expect that by the time of the symposium we will have been able to run more comprehensive experiments and report results with a much more representative set of users and on a number of different paths.

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