Partner-Aware Control Framework for pHRI Leveraging Physical Interactions

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***Abstract*— Studying physical interaction with a robot by an external agent, like a human or another robot, without considering the dynamics of both the systems involved leads to many shortcomings in fully understanding and exploiting the interaction. In this work, we present a coupled-dynamics formalism followed by a sound approach in exploiting helpful interaction with a robot. Furthermore, we present a task-based partner-aware robot control techniques. We validate the theoretical results by conducting experiments in which an external agent and a humanoid robot are involved in physical interaction.**

I. INTRODUCTION

Robots existed as separate entities till now but the horizons of a symbiotic human-robot partnership are impending. In particular, application domains like elderly care, collaborative manufacturing, collaborative manipulation, etc., are considered the need of the hour. Across all these domains, it is crucial for robots to physically interact with humans to either assist them or to augment their capabilities. Such *human in the loop* physical human-robot interaction (pHRI) scenarios demand careful consideration of both the human and the robot systems while designing controllers to facilitate robust interaction strategies for successful task completion.

More specifically, the interaction between a human and a humanoid robot is particularly challenging because of the complexity of the robotic system [1]. Unlike fixed base industrial robots, humanoid robots are designed as floating base systems to facilitate anthropomorphic navigational capabilities. In general, robotic controllers [2] [3] are build to be robust to any external perturbations and hence they are often blind to any helpful interaction a human is trying to have with the robot to help achieve its task.

The knowledge of human intent is a key element for the successful realization of pHRI. The choice of a communication channel is directly related to intent measurement and affects the robot's ability to understand human intent. A myriad of technologies are used as interfaces for different applications of pHRI like electroencephalography (EEG), electromyography (EMG), force myography (FMG), force/torque sensors, computer vision based techniques etc. Often times, the use of a single mode of an interface is limiting. We believe there is an impending change in this paradigm and the future technologies of pHRI will leverage on getting as much holistic information as possible from humans involved in pHRI, especially for domains like collaborative manufacturing. Having both the kinematic quantities like joint positions and velocities and dynamic quantities like joint accelerations and torques of the human will enable real-time monitoring of the human to build robust controllers for successful task completion taking into account the physical interactions between the human and the robot.

II. MODELING

The human-related notations are denoted with $\mathbb{double-bold}$ terms while the robot-related notations are denoted with "$\mathrm{straight}$" terms, and notations that apply to both the systems are denoted with $slanted$ terms. In addition, composite matrices are denoted with $\boldsymbol{BOLD}$ terms. A typical physical human-robot interaction scenario is shown in Fig. 1. There are two agents: the human, and the robot. Both agents are physically interacting with the environment and, in addition, are also engaged in physical interaction with each other.

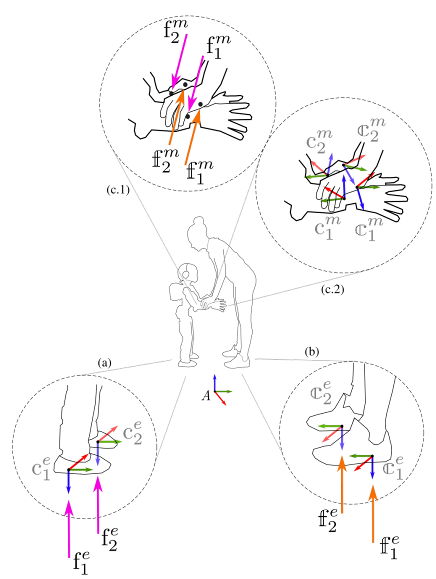

Fig. 1: A typical human-robot interaction scenario

We consider both the human and the robot as multi-body *free-floating* mechanical systems. This assumption serves as a rough approximation when formulating physical human-robot interaction dynamics and allow us to synthesize robot controllers optimizing both human and robot variables. The equations of motion describing the dynamics of the human and the robotic agents respectively are:

$$\mathbb{M}(\mathbb{q})\dot{\nu} + \mathbb{C}(\mathbb{q}, \nu)\nu + \mathbb{G}(\mathbb{q}) = \mathbb{B}\tau^{\mathrm{H}} + \mathbb{J}^T\mathbb{f}^* \tag{1a}$$

$$\mathrm{M}(\mathrm{q})\dot{\nu} + \mathrm{C}(\mathrm{q}, \nu)\nu + \mathrm{G}(\mathrm{q}) = \mathrm{B}\tau^{\mathrm{R}} + \mathrm{J}^T\mathrm{f}^* \tag{1b}$$

The contact constraints present in the combined system can be represented in the compact form as:

$$\dot{\boldsymbol{Q}}\boldsymbol{V} + \boldsymbol{Q}\dot{\boldsymbol{V}} = 0 \tag{2}$$

On combining the equations (1a), (1b), and (2), we can write the total interaction wrench of the coupled system as:

$$\boldsymbol{f}^* = \boldsymbol{G}_1\tau^{\text{H}} + \boldsymbol{G}_2\tau^{\text{R}} + \boldsymbol{G}_3(\mathbb{q}, \mathrm{q}, \mathbb{\nu}, \nu) \tag{3}$$

Through coupled-dynamics, equation (3) highlights that the external wrenches are a function of system configuration $\mathbb{q}$, q, system velocity $\mathbb{\nu}$, ν, and joint torques τ^{H}, τ^{R}. This can be represented as a function $\boldsymbol{f}^* = g(\mathbb{q}, \mathrm{q}, \mathbb{\nu}, \nu, \tau^{\text{H}}, \tau^{\text{R}})$.

III. Partner-aware control

Let $\chi \in \mathbb{R}^p$ be a robot-related quantity of dimension p that is assumed to have a linear map to the robot's velocity, i.e.:

$$\chi = \mathrm{J}_\chi(\mathrm{q})\ \nu \tag{4}$$

Let χ_d denote the desired value of χ, and $\widetilde{\chi} = \chi - \chi_d$ the error to be minimized. On time differentiating (4) and by substituting the robot acceleration $\dot{\nu}$ with its expression obtained from the model (1b) one can observe that the acceleration $\dot{\chi}$ depends upon the robot torques τ^{R}, namely, $\dot{\chi} = \dot{\chi}(\tau^{\text{R}})$. Then, a classical feedback linearization approach [4] for the control of the robot quantity χ consists of finding the robot joint torques τ^{R} such that

$$\dot{\chi} = \dot{\chi}_d - k_d\ \widetilde{\chi} - k_p \int_0^t \widetilde{\chi} ds, \quad k_d, k_p > 0 \tag{5}$$

In the language of optimization theory, the above feedback linearization control task can be framed in the following optimization problem

$$\tau^{\text{R}*} = \arg\min_{\tau^{\text{R}}} |\dot{\chi}(\tau^{\text{R}}) - \dot{\chi}_d + k_d\widetilde{\chi} + k_p \int_0^t \widetilde{\chi} ds|^2 \tag{6a}$$

$$s.t.$$

$$\boldsymbol{M}\dot{\boldsymbol{V}} + \boldsymbol{h} = \boldsymbol{B}\boldsymbol{\tau} + \boldsymbol{J}^T\boldsymbol{f}^* \tag{6b}$$

$$\dot{\boldsymbol{Q}}\boldsymbol{V} + \boldsymbol{Q}\dot{\boldsymbol{V}} = 0 \tag{6c}$$

This approach is fundamentally agnostic to any interaction from an external agent. This is evident from Eq. (5) since no human quantity appears on the right-hand side of this equation. This motivates us to propose partner-aware robot control techniques that *exploit* help provided by an external agent during the physical interaction. Certainly, instead of completely canceling out any external interaction by the feedback control action, it is gainful and desirable to *exploit* it to accomplish the robot's task. This poses, however, the question of characterizing and quantifying human help with respect to the robot task.

Typically, interaction wrench *estimates* from the robot are used as human intent information. However, in a coupled system, wrench estimates introduce an algebraic loop in the control design as they are computed using the robot joint torques [5]. Instead, a sound approach is to leverage the joint torques of the human as they are largely self-generated and self-regulated. Additionally, considering the joint torques opens new possibilities for our future work to investigate and optimize human ergonomics. The following lemma proposes partner-aware control laws that exploit the human contribution towards the achievement of robot's control objective, thus actively taking into account the physical human-robot interaction.

Lemma 1: Assume that the control objective is to asymptotically stabilize the following point

$$\left(\widetilde{\chi}, \int \widetilde{\chi} ds\right) = (0, 0) \tag{7}$$

Apply the following robot torques to the robot system (1b)

$$\tau^{\text{R}} = -\boldsymbol{\Delta}^\dagger\ [\ \Lambda\ +\ K_D\ \widetilde{\chi}\ +\ max(0, \alpha)\ \widetilde{\chi}^{\|}\ ] \tag{8}$$

with

- $\boldsymbol{\Delta} = K_d\ \mathrm{J}_\chi \mathrm{M}^{-1}[\mathrm{B} + \mathrm{J}^T\bar{\boldsymbol{G}}_2] \in \mathbb{R}^{p \times \mathrm{n}}$
- $K_D \in \mathbb{R}^{p \times p}$ is a symmetric, positive-definite matrix
- $\alpha \in \mathbb{R}$ is a component proportional to the human joint torques τ^{H} projected along $\widetilde{\chi}^{\|}$ i.e., the direction parallel to $\widetilde{\chi}$

Assume that the matrix $\boldsymbol{\Delta}$ is full rank matrix $\forall\ t \in \mathbb{R}^+$. Then

- The trajectories $(\widetilde{\chi}, \int \widetilde{\chi} ds)$ are globally bounded
- The equilibrium point (7) is stable

IV. EXPERIMENTS

In case of complex humanoid robots, state-of-the-art whole-body controllers often consider controlling the robot momentum [2] and accordingly the Eq. (4) becomes,

$$\mathrm{L} = \mathrm{J}_{cmm}(\mathrm{q})\ \nu \tag{9}$$

where J_{cmm} is the centroidal momentum matrix. The primary control objective of the robot is momentum control while performing the stand-up from a chair task. The robot will make use of any assistance provided by the interacting agent to achieve this task. Considering the human model as a multi-body mechanical system of rigid links allows us to use another humanoid robot in place of a human without the loss of integrity of the experiment. So, we validate our control framework with both physical human-robot interaction and physical robot-robot interaction experiments.

References

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