Partner-Aware Humanoid Robot Control: from Robot-Robot collaboration to Human-Robot Collaboration and Ergonomy Control

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I. Introduction

The success of robots in real-world applications is largely dependent on their ability to physically interact with the environment. A robotic agent should be endowed with the capabilities that exhibit robustness to unwanted physical interactions and at the same time facilitate intentional interactions. Recent research in the field of human-robot collaboration paved the way to a new generation of lightweight and compliant robots that are designed to operate alongside humans in a cage-free environment. Application domains like collaborative manufacturing and elderly assistance will have a direct impact by the future advances in the field of robotics, raising the attention both in industry and in the scientific community resulting in many international research projects.

Safety and flexibility are two of the main aspects concerning physical human-robot collaboration systems [1]. Despite the recent growth in automation, the cognitive skills and dexterity of humans are still essential components to achieve complicated tasks. Accordingly, collaborative robots need to be compliant to human flexibility, and at the same time guarantee an optimal working condition for the execution of a given task. Concerning safety, the requirements are not limited to just avoiding potential collisions or excessive impact forces, but also to avoid work-related musculoskeletal disorders that can arise due to repeated excessive effort or extreme posture [2]. Collaborative robots should guarantee both optimal task execution and human safety through active monitoring and control of the kinematic state and the dynamic state of the human.

Humanoid robot platforms are designed based on the idea of anthropomorphism, and are typically embedded with a set of distributed sensors that allows environmental perception and robot state estimation. The actuators allow to control the robot state and to interact with the environment. State-of-the-art whole-body robot controllers can achieve different task by controlling the robot state and maintaining robot stability by suppressing any external disturbances. In simple applications, the interaction with inanimate object can be simply model in order to achieve the desired task relying only on robot actions. However, in case of more challenging scenario involving multiple agents collaborating for achieving a common task, strategies for shared control that can exploit the physical interactions are crucial for successful task completion. Physical Robot-Robot and Human-Robot Collaboration scenarios, such as the collaborative lifting shown in figure 1, are examples of such involving tasks. In particular, the presence of a human agent makes the scenario more challenging since the human is not directly controlled, and perceiving human state and intentions is not trivial [3].

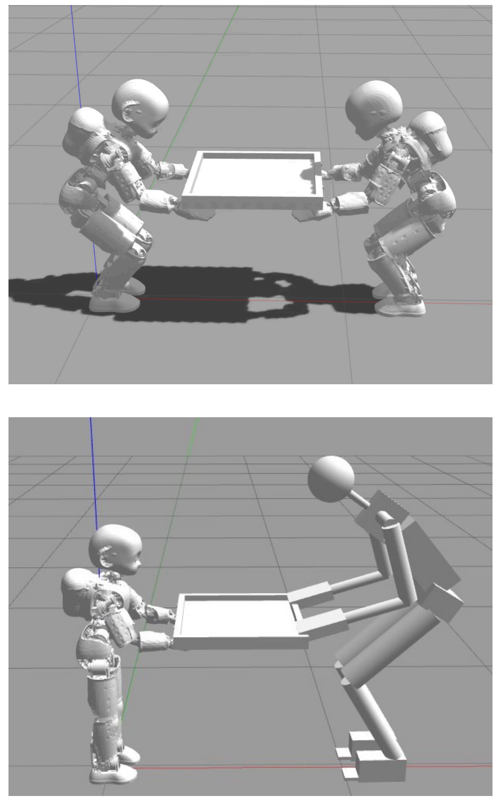

Fig. 1: Simulation of a collaborative lifting scenario. On top, the task is performed by two robotic agents. On the bottom, the same task is performed replacing one of the two robots with a human.

Different control framework for collaborative control have been proposed. If in some case the partner is simply considered as an external disturbance, in other framework the partner behaviour is exploited. In case of human partner, this

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is often possible thanks to modern wearable technologies that allows retrieving online both human kinematic and dynamic state. Furthermore, real-time accurate estimation of human state opens up new possible scenario in physical human-robot interaction where the control of human ergonomy is achieved.

This article draws from our studies towards the design and the implementation of robust interaction strategies for humanoid robots. In particular, starting from the results in physical robot-robot collaboration, we aim to design robot controller able to exploit the help of the human partner and optimize its ergonomic state. The outcome of this research can have a possible impact in different application domains such as assistive technologies, collaborative manipulation and rehabilitative robots.

II. Background and Modelling

In a typical physical interaction scenario, the dynamics of the both the agents involved play a crucial role in describing the system evolution. In order to model the interaction more concretely, the dynamics of both the systems have to be considered together rather than in isolation. In recent work we have presented a coupled-dynamics formalism that takes into account the dynamics of the combined system [4].

A simple two agents interaction scenario is shown in Figure 2. Modelling both the agents as multi-body mechanical system, the coupled dynamics is described with Newton-Euler formalism by the following set of equations equation:

$$\begin{bmatrix} M & 0 \\ 0 & \mathbb{M} \end{bmatrix} \begin{bmatrix} \dot{\nu} \\ \dot{\mathbb{\nu}} \end{bmatrix} + \begin{bmatrix} h \\ \mathbb{h} \end{bmatrix} = \begin{bmatrix} B & 0 \\ 0 & \mathbb{B} \end{bmatrix} \begin{bmatrix} \tau \\ \mathbb{\tau} \end{bmatrix} + \mathbf{Q}^T \mathbf{f} \tag{1a}$$

$$\mathbf{Q} \begin{bmatrix} \nu \\ \mathbb{\nu} \end{bmatrix} = 0 \tag{1b}$$

where "$straight$" terms describe the dynamics of the robot, "$\mathbb{double}$" terms describe the dynamics of the human, and "**bold**" terms describe the quantities coupling the two system. In particular $\mathbf{Q}$ is a matrix that couple the jacobian matrices of the two system in the contact points, and the vector $\mathbf{f} = \begin{bmatrix} f_1^{eT} & f_2^{eT} & \mathbb{f}_1^{eT} & \mathbb{f}_2^{mT} & f_1^{mT} \end{bmatrix}$ contains all information regarding interaction wrenches taking into account the fact that at the hands the two system are coupled, i.e. $f_1^m = -\mathbb{f}_1^m$ and $f_2^m = -\mathbb{f}_2^m$. The set of equation (1a) describes the evolution of the dynamic quantities of the two systems, and (1b) describes the kinematic velocity constraints for both the feet and the hands.

III. Partner-Aware Humanoid Robot Control

Unlike traditional industrial robots which are fixed base by design, humanoid robots are floating base systems with navigational capabilities. The aspect of balancing has received a lot of attention in the humanoid robotics community and several efforts went into building controllers that ensure stable robot behavior. More recently momentum-based whole-body control proved to be a robust approach and several successful applications have been realized showing an improved compliance of the system [5] [6].

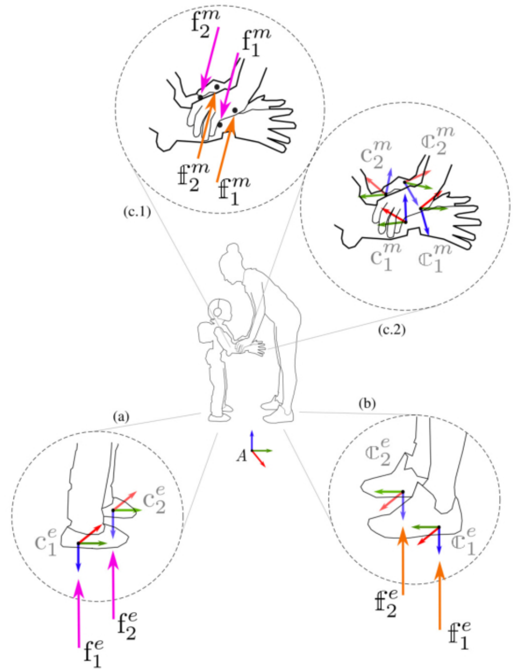
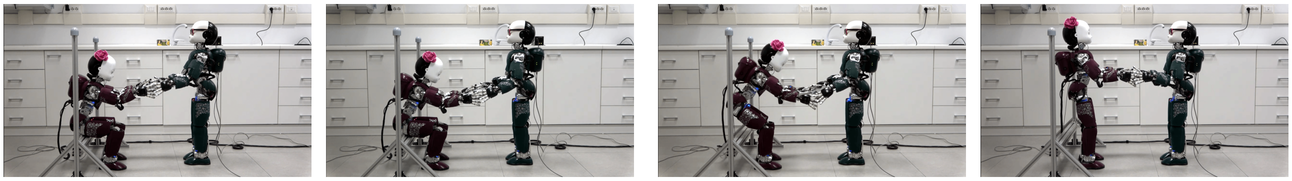


Fig. 2: Human-robot interaction scenario highlighting the wrenches exchanged among the two agents and with the environment.

State-of-the-art whole-body controllers are mainly based on feedback linearization. When considering collaborative applications, the main drawback of feedback linearization approach is that the closed loop dynamics is independent from any partner related quantity. As a consequence, the robot behavior is invariant with respect to interactions since those are canceled out by the feedback control action. In some collaborative applications force/torque sensors mounted on the robots are involved in robot control as they facilitate direct monitoring and regulation of the interaction wrenches between the human and the robot [7][8][9]. However, not only the interaction wrenches, but the whole dynamics of the agents involved play a crucial role in describing the interaction and the dynamics of both the systems have to be considered together rather than in isolation.

Our recent work takes into account the dynamics of the combined system for controlling the robot in a collaboration scenarios [4]. The achievement of this controller is accomplished by exploiting the partner interaction, namely, the controller renders the robot compliant to the partner actions, and takes advantages of this collaboration to achieve the robot control objective. An experimental setup where two iCub humanoid robots are involved in a collaborative scenario with physical interactions is highlighted in Figure 3. The purple robot is torque controlled and is expected to perform a stand-up task with assistance from the green robot that is position controlled and executes pre-programmed



(a) (b) (c) (d)

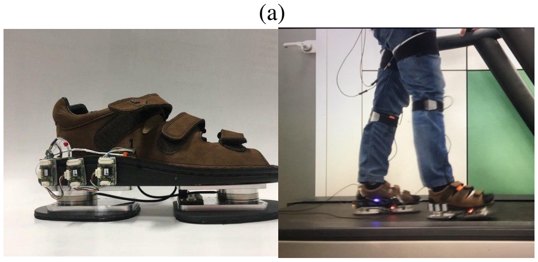
Fig. 3: Stand-up experimental scenario with two iCub robots involved in physical interaction.

movements that mimic pull-up assistance. The control laws for the torque-controlled robot are formulated by considering the state and the dynamics of both the robots and modelling the interactions among the two. The results presented in [4] shows the effect of partner-aware control in minimizing the energy function of the system.

IV. Human State Estimation

Moving from a robot partner to a human partner raise the problem of retrieving human data measurements i.e. human joint positions, velocities, accelerations, and torques in real-time. Human motion tracking using computer vision techniques is a fairly advanced technology that can run even on a smart device. However, they are computationally intensive and can not ensure high frequency data for time-critical applications, and moreover they can fail due to occlusions. For those reason we rely on a wearable suit with distributed Inertial Motion Units (IMUs), as shown in Figure 4a, whose output is used to compute the human state in real-time through dynamical inverse kinematics optimization [10]. Furthermore, we developed sensorized force/torque wearable shoes, as shown in Figure 4, used to perform floating-base estimation of human joint torques [11].

(a)



(b) (c)

Fig. 4: (a) Wearable suit with distribute IMU sensors. (b),(c) Sensorized force/torque wearable shoes

V. Ergonomy Control in Human-Robot Collaboration

The control frameworks proposed in Section III applies both for robot-robot and human-robot collaboration, and presents a way to exploit efficiently the physical collaboration between two agents. An extension of those controllers can give the possibility to achieve the stabilization of human related quantities with possible implication in many interesting applications. In human-robot collaboration, for example, by controlling the human posture it is possible to reduce the risk of muskoloskeletal disorders or injuries. In this context, the so called ergonomy control objectives can be achieved through the control of human state for optimizing the subject ergonomy. This is possible because the full dynamics of the human partner is considered in the controller, and it can be controlled thanks to the redundancy of the robot control input τ that can be projected into human related quantites.

There exists different indices for evaluating human ergonomy in literature, and some of them are currently recognized by international organizations [12]. Most of those indices are based on some of the following objectives: reducing muscular effort, avoiding awkward posture, reducing excessive motion, and avoid near-extreme range of motion movement. In order to include those principles in the control framework, it is necessary to formulate an optimization problem where those tasks are mapped into human kinematic and dynamic quantities of the human. In particular, the muscular effort can be directly related to the human joint torques ($\mathbb{\tau}$), while the control posture and motion are related to kinematic quantities ($\mathbb{q}, \mathbb{\nu}$). Hence, we propose the following ergonomy objectives that can be included in partner-aware robot controller for human-robot collaboration:

- minimize the human torque

$$min_{\mathbb{\tau}} \| K_{\mathbb{\tau}} \mathbb{\tau} \| \tag{2}$$

- maintain the posture close to a desired posture $\mathbb{q}_{des}$

$$min_{\mathbb{\tau}} \| K_{\mathbb{q}} (\mathbb{q} - \mathbb{q}_{des}) \| \tag{3}$$

- minimize the joint velocities

$$min_{\mathbb{\nu}} \| K_{\mathbb{\nu}} \mathbb{\nu} \| \tag{4}$$

where the matrices $K_{\mathbb{T}}, K_{\mathbb{q}}, K_{\mathbb{v}}$ weight each quantity accordingly to risk related to each joint. Those optimization problem can be combined a single optimization problem of an ergonomy index that depends on robot action $\mathbb{E} = \mathbb{E}(\tau)$.

The design of humanoid robot controller for physical human robot collaboration can then be extended by adding the ergonomy objective task to the shared collaborative task and the momentum-based balancing task. Considering the collaborative lifting scenario shown in Figure 1, this can be achieved trough a stack of task optimization design as follow:

$$\underset{\tau}{\text{minimize}} \quad \left\|\mathbb{E}(\tau)\right\| \tag{5a}$$
$$\text{subject to} \quad \dot{\mathbf{H}}(\tau) = \dot{\mathbf{H}}^{*} \tag{5b}$$
$$\dot{\mathrm{v}}_B(\tau) = \dot{\mathrm{v}}_B^{*} \tag{5c}$$

where $\mathbf{H}$ denotes the centroidal momentum of the coupled system, and v_B denotes the rigid body velocity of the lifted load.

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