The Human Wearable Perception System: a Human-Robot Collaboration Application

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I. Introduction

The human-robot collaboration (HRC) is more and more requested in several occupational fields, e.g., in assembly-line factories, in medical rehabilitation centers for patients or for domestic assistance. Although today's robots are equipped with sophisticated sensors, their collaborative success is not always guaranteed by the onboard technologies. The perception that the robots have of the human collaborators during a shared task is very limited due to unpredictability of the human movements [1]. For this reason we introduced a novel framework endowing robots with the ability to perceive humans while fulfilling a cooperative task. The framework is composed of $i)$ a wearable sensor system (i.e., the Xsens motion tracking system, a pair o portable sensorized shoes equipped with 6-axis force/torque sensors and tactile insoles [2], developed at Istituto Italiano di Tecnologia) and $ii)$ a software architecture implementing a real-time whole-body kinematics and dynamics estimation. Within this framework, the robot perceives $i)$ the position and motion of the human, $ii)$ the exchanged contact forces and $iii)$ the human joint torques for the task ergonomy control [3]. During the HRC, robots can make the human ergonomics better by embodying the human estimated quantities and adjusting their collaborative interaction strategy.

II. Simultanueous Kinematics and Dynamics Human Estimation

We implemented a probabilistic Maximum-A-Posteriori (MAP) algorithm to compute the simultaneous floating-base estimation of the human whole-body kinematics and dynamics (i.e., joint torques, internal forces exchanged across joints, external forces acting on links). The algorithm is based on the modelling of the human body as a floating-base dynamic system of rigid links connected by joints,

$$\boldsymbol{M}(\boldsymbol{q})\dot{\boldsymbol{\nu}} + \boldsymbol{C}(\boldsymbol{q},\boldsymbol{\nu})\boldsymbol{\nu} + \boldsymbol{G}(\boldsymbol{q}) = \boldsymbol{B}\boldsymbol{\tau} + \mathbf{J}^\top(\boldsymbol{q})\ \boldsymbol{f}^{\text{x}}\ , \tag{1a}$$

$$\mathbf{J}(\boldsymbol{q})\dot{\boldsymbol{\nu}} + \dot{\mathbf{J}}(\boldsymbol{q})\boldsymbol{\nu} = \mathbf{0}\ , \tag{1b}$$

where $\boldsymbol{M}$ and $\boldsymbol{C}$ are the mass and Coriolis effect matrix, respectively. $\boldsymbol{G}$ is a term accounting for the gravity effect. $\boldsymbol{B}$ is a selector matrix for the joint torques $\boldsymbol{\tau}$. $\mathbf{J}$ is the Jacobian operator that maps the system velocity with the velocity of the link where is acting the external force $\boldsymbol{f}^{\text{x}}$. The system configuration is represented by $\boldsymbol{q} = (\boldsymbol{q}_b, \boldsymbol{s})$, being $\boldsymbol{q}_b$ the pose of the base with respect to (w.r.t) a generic inertial frame $\mathcal{I}$ and $\boldsymbol{s}$ the joint position vector capturing the topology of the system. Terms $\dot{\boldsymbol{\nu}}$ and $\boldsymbol{\nu}$ are the acceleration and velocity of the system, respectively. In particular, $\boldsymbol{\nu} = (\boldsymbol{v}_b, \dot{\boldsymbol{s}})$ where $\boldsymbol{v}_b$ is the base velocity expressed w.r.t. $\mathcal{I}$ and $\dot{\boldsymbol{s}}$ is the joint velocities vector. Contact constraints are captured in Eq. (1b) .

A model-based algorithm which exploits the velocity correction and differential kinematics integration has been implemented to compute the human kinematics [4]. To solve the dynamic estimation problem, the overall system in (1) is rearranged to an equivalent compact matrix form [5]:

$$\begin{bmatrix}\boldsymbol{Y}(\boldsymbol{s})\\ \boldsymbol{D}(\boldsymbol{s})\end{bmatrix}\boldsymbol{d} + \begin{bmatrix}\boldsymbol{b}_Y(\boldsymbol{s},\dot{\boldsymbol{s}})\\ \boldsymbol{b}_D(\boldsymbol{s},\dot{\boldsymbol{s}})\end{bmatrix} = \begin{bmatrix}\boldsymbol{y}\\ \mathbf{0}\end{bmatrix}\ , \tag{2}$$

where $\boldsymbol{Y}$ is a matrix taking into account the measurements of the sensors, $\boldsymbol{D}$ is a matrix for the system constraints. Bias terms $\boldsymbol{b}_Y$ and $\boldsymbol{b}_D$ are related to the above-listed matrices, respectively. The vector $\boldsymbol{d}$ embodies kinematics and dynamics quantities of the model. The vector $\boldsymbol{y}$ contains values measured via sensors, i.e., IMUs accelerations and external forces, $\boldsymbol{y} = \begin{bmatrix}\boldsymbol{a}_{\text{IMUs}} & \boldsymbol{f}^{\text{x}}\end{bmatrix}^\top$.

The solution of the problem is provided by solving the system in (2) for the vector $\boldsymbol{d}$. The estimator maximizes the probability of $\boldsymbol{d}$ given the measurements reliability. The estimator, therefore, looks for the mean of a conditional probability, i.e., $\boldsymbol{d} = \boldsymbol{\mu}_{d|y}$ in the Gaussian domain, and its covariance $\boldsymbol{\Sigma}_{d|y}$,

$$\left[\boldsymbol{\mu}_{d|y}, \boldsymbol{\Sigma}_{d|y}\right] = \arg\max_{\boldsymbol{d}} p(\boldsymbol{d}|\boldsymbol{y})\ . \tag{3}$$

A Stack-of-Tasks variant has been recently added to the MAP computation [6]. The variant solves system in Eq. (2) as a stack of two tasks, by decoupling the estimation of the torques from the internal wrenches.

III. A human-robot collaboration application

In the typical HRC scenario, the dynamics of both the human and the robot plays a crucial role in describing the system evolution. In recent work, we have presented a coupled-dynamics formalism that takes into account the dynamics of the combined system for controlling the robot in a collaboration scenarios [3]. Human quantities are provided by a

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Fig. 1: Experimental scenario with the iCub humanoid robot standing-up with the help of a sensorized human.

C++ based software architecture designed for the real-time $i)$ acquisition of human data and $ii)$ estimation of the whole-body kinematics and dynamics. The architecture streams the output through the YARP middleware [7] and is suitable for real-time visualization tools (e.g., ROS RViz). An experimental setup where the torque-controlled iCub humanoid robot [8] is involved in a collaborative scenario with a sensorized human is highlighted in Figure 1. The goal was to perform a stand-up task with the human's assistance. The achievement of the robot controller is accomplished by exploiting the partner interaction, i.e., the controller makes the robot compliant to the human actions, and takes advantages of the collaboration to achieve the robot control objective by minimizing the energy function of the system. An extension of HRC controllers is the possibility to achieve the stabilization of the human-related quantities during the interaction since the full dynamics of the human partner is embodied in the robot controller. The extension is suitable for different application fields, e.g., in industrial environments to reduce the risk of musculoskeletal disorders or injuries by controlling the human posture and the whole-body load distribution. It is, therefore, possible to define ergonomy control objectives by optimizing human ergonomy achieved via the control of human state. Moreover, when humans interact with robots, optimal ergonomic interactions shall minimize metrics that consider also the robot agent. Different indices for evaluating human ergonomy in literature are currently recognized by international organizations [9]. Human energy expenditure has been used to evaluate ergonomics in workplaces [10], and it was often used in human-robot interactions scenario [11]–[13]. Similarly, robot energy consumption optimization is a requirement for robotics application. Accordingly to the rigid-body modelling in Eq. (1) , energy expenditure is directly related to joint torques both for human and robot. In order to embody those principles in the control framework, it is required to set an optimization problem that takes into account the dynamics of both the agents, in order to minimize joint torques. The optimization can be decomposed into two sub-problems. The first problem is to find the optimal ergonomic configuration for the system, and can be solved during the task planning phase to drive the robot motion. The second problem is the optimization of the interaction forces during the task execution, and can be solved online thanks to the human perception system.

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