A Model-Based Residual Approach for pHRI in Industrial Setting: a Possible Extension to Human-Humanoid collaboration

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Extended Abstract

During industrial operations it may be required the intervention of a human operator in order to perform some quick and simple maneuvers, which should not require re-programming the robot. For instance, during polishing operations a force is typically exerted by the human on the surface, while the robot holds the part to be polished. In some cases, it could be useful to reorient the part by manually pushing the robot structure.

Both the force at the end-effector and the force acting on the robot structure yield an additional torque at the robot joints, as

$$\boldsymbol{\tau}_{ext} = \boldsymbol{\tau}_e + \boldsymbol{\tau}_c = \boldsymbol{J}_e^T(\boldsymbol{q})\boldsymbol{F}_e + \boldsymbol{J}_c^T(\boldsymbol{q})\boldsymbol{F}_c, \quad (1)$$

where, for a n-DoF robot, $\boldsymbol{\tau}_{ext} \in \mathbb{R}^n$ is the total external torque at the joints, whose two components $\boldsymbol{\tau}_e \in \mathbb{R}^n$ and $\boldsymbol{\tau}_c \in \mathbb{R}^n$ are, respectively, the torque at joint level due to the force exerted to the end-effector $\boldsymbol{F}_e \in \mathbb{R}^6$ and the torque at joint level due to the force at the contact point $\boldsymbol{F}_c \in \mathbb{R}^6$; finally, $\boldsymbol{J}_e \in \mathbb{R}^{6\times n}$ and $\boldsymbol{J}_c \in \mathbb{R}^{6\times n}$ are, respectively, the jacobian at the end-effector and at the contact point along the structure.

In order to separate the two quantities $\boldsymbol{\tau}_e$ and $\boldsymbol{\tau}_c$, the values of $\boldsymbol{F}_e$ and $\boldsymbol{F}_c$ have to be known, as well as the link where the contact occurs, which is necessary to compute the Jacobian matrix $\boldsymbol{J}_c$. While, moreover, the force $\boldsymbol{F}_e$ can be retrieved thanks to a force sensor mounted onto the end-effector, the force $\boldsymbol{F}_c$ is hardly achievable, even if the contact link can be identified using an external sensor, like a depth camera [1].

The idea is to generate self-motions of the robot as the human operator pushes the manipulator structure, while keeping fixed the position of the end-effector, relaxing its orientation. Separating the Jacobian matrix $\boldsymbol{J}_e(\boldsymbol{q})$ into its position and orientation components as

$$\boldsymbol{J}_e(\boldsymbol{q}) = \begin{pmatrix} \boldsymbol{J}_p(\boldsymbol{q}) \\ \boldsymbol{J}_o(\boldsymbol{q}), \end{pmatrix} \quad (2)$$

and assuming that the robot joints are controlled by velocity references (kinematic control), the following control law can be adopted, in order to provide the proper self-motion:

$$\dot{\boldsymbol{q}} = \boldsymbol{J}_p^{\#}\boldsymbol{K}_p(\boldsymbol{p}_d - \boldsymbol{p}) + (\boldsymbol{I} - \boldsymbol{J}_p^{\#}\boldsymbol{J}_p)\boldsymbol{K}_r\boldsymbol{r}, \quad (3)$$

where $\boldsymbol{K}_p$ and $\boldsymbol{K}_r$ are gain matrices and $\boldsymbol{p}_d$ is the desired end-effector position; the vector $\boldsymbol{r} \in \mathbb{R}^n$ is the residual vector [2], as:

$$\begin{aligned}\boldsymbol{r}(t) \;&= \boldsymbol{K}_i \Big(\boldsymbol{M}(\boldsymbol{q})\dot{\boldsymbol{q}} - \textstyle\int_0^t \Big(\boldsymbol{C}^T(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \\ &-\boldsymbol{g}(\boldsymbol{q}) + \boldsymbol{\tau} + \boldsymbol{\tau}_e - \boldsymbol{r}\Big)\, ds\Big)\,,\end{aligned} \quad (4)$$

where where $\boldsymbol{M}(\boldsymbol{q}) \in \mathbb{R}^{n\times n}$ is the inertia matrix, $\boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}}) \in \mathbb{R}^{n\times n}$ is the Coriolis and centrifugal forces matrix, $\boldsymbol{g}(\boldsymbol{q}) \in \mathbb{R}^n$ is the gravity vector, $\boldsymbol{\tau} \in \mathbb{R}^n$ is the vector of motor torques and $\boldsymbol{K}_i$ a proper gain matrix. Please note that the contribution of the force at the end-effector is subtracted from the residual driving the null-space joint velocities.

The vector $\boldsymbol{r}$ is the residual estimating the contact torque $\boldsymbol{\tau}_c$ acting at the joint level. Note that this method is applicable even without the need of a joint torque sensor, provided that one has a reliable dynamic model of the robot and information on the motor currents. We successfully tested this contact force detection method, first with a 7R KUKA LWR 4+ arm, for which we have a validated dynamic model [3] and joint torque sensors available. Next, we implemented the control law (3) on a 6R UR10 manipulator, in which only joint position and motor current sensors are present. We successfully identified its dynamic model, including friction (see Fig. 1), and we were able to compute the residual vector (4), as reported in Fig. 2.

The experiment reported in Fig. 3 shows the effect of the control algorithm when an operator is in contact with the tip of the end effector only (around sec. 5-10), when the operator is in contact with the robot structure only (around sec. 10-15), and when the operator is in contact both with the end-effector and the robot structure (around sec. 15-25). In all cases, the end-effector position remains still (first panel); if the estimated residual exceeds a given threshold, the control law computes the driving part of the residual (given the measures of the force sensor), and moves the robot structure according to the operator's will.

This approach may be applied to human-humanoid collaboration. The use of the residual for measuring contacts in humanoids application has been discussed by Flacco et. al [4]. Exploiting the control law (3) and equipping the humanoid with force sensors (for instance, at the hands), it would be possible a cooperation between a human and the humanoid or between two humanoids in several applications, as for instance moving a large object which needs to be kept from both edges (like a board). In fact, while the two agents are moving in an environment, holding up the object, a possible collision between the robot and the environment

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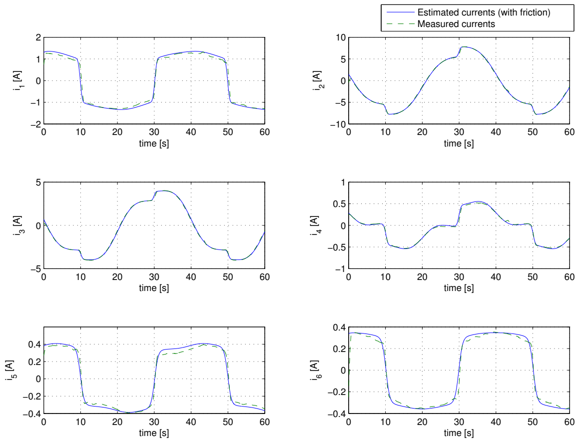

Fig. 1. Comparison between measured (dashed-green) and estimated (continuous blue) joint currents, considering friction.

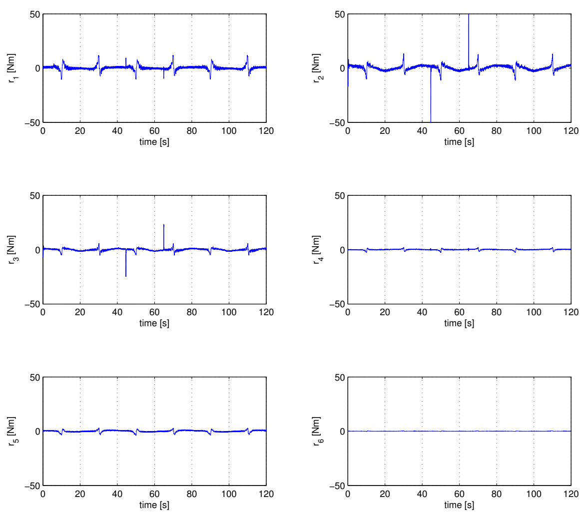

Fig. 2. Residual signal during motion. The human operator exerts a contact force, with an impulsive but mild touch, at $t = 45$ s and $t = 65$ s in opposite directions. The contact is detected by the residual signal, which exhibits two peaks in correspondence of the collisions.

can be managed by the algorithm, exploiting the redundancy – like for the industrial robot case – or changing the motion of the humanoid.

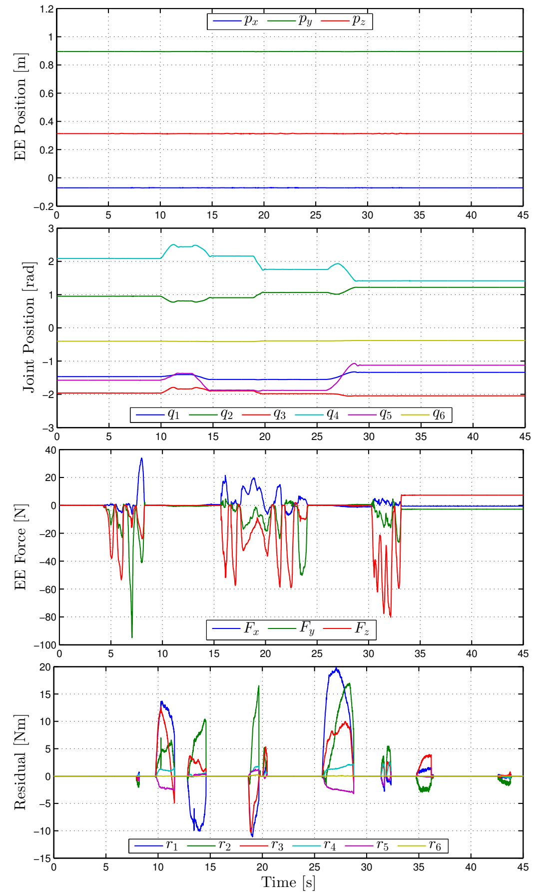

Fig. 3. Interaction control experiment. Starting from the top: end-effector Cartesian position, joint configuration, contact force at E-E measured by the F/T sensor, and residual components.

REFERENCES

[1] E. Magrini, F. Flacco, and A. De Luca, "Control of generalized contact motion and force in physical human-robot interaction," in *Proc. IEEE Int. Conf. on Robotics and Automation*, 2015, pp. 2298–2304.

[2] A. De Luca, A. Albu-Schäffer, S. Haddadin, and G. Hirzinger, "Collision detection and safe reaction with the DLR-III lightweight robot arm," in *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, 2006, pp. 1623–1630.

[3] C. Gaz, F. Flacco, and A. D. Luca, "Identifying the dynamic model used by the KUKA LWR: A reverse engineering approach," in *Proc. IEEE Int. Conf. on Robotics and Automation*, 2014, pp. 1386–1392.

[4] F. Flacco, A. Paolillo, and A. Kheddar, "Residual-based contacts estimation for humanoid robots," in *2016 IEEE-RAS 16th International Conference on Humanoid Robots (Humanoids)*, Nov 2016, pp. 409–415.