Avoiding undesired human interaction wrenches for estimation in human-robot manipulation tasks

Denis Ćehajić, Pablo Budde gen. Dohmann, and Sandra Hirche

***Abstract*—Knowing accurately the kinematic and dynamic parameters of a manipulated object is required for common coordination strategies in physical human-robot interaction. Parameter bias may disturb the human during interaction and bias the recognition of the human motion intention. This work presents a strategy allowing the tracking of human motion and inducing the motions necessary for identification. Such motions are projected in the null space of the partial grasp matrix, relating the human and the robot redundant motion directions, to avoid the disturbance of the human motion. The approach is evaluated in a human-robot object manipulation setting.**

I. INTRODUCTION

Physical human-robot collaboration (pHRI) is envision in multiple application domains in the future, such as industrial, domestic- and service-related. As the human and the robot are directly coupled, the behavior of the robot directly influences that of the human and vice versa. The interaction of the robot during cooperation with the human is achieved through the impedance/admittance control in combination with the object dynamics model [1]–[3]. Wrenches applied on the object are usually transformed to the robot frame using the relative kinematics. Desired wrenches needed to achieve a desired motion are calculated through the inverse dynamics model [1], [2]. Any bias in either the relative kinematics, i.e. relative displacement and orientation of the frames, and/or the object dynamic parameters, i.e. mass, center of mass, and moments of inertia, results in incorrectly calculated robot wrenches, which may disturb the human partner during interaction or when performing a desired motion [4], [5].

Since in many real-life physical human-robot interaction applications the relative kinematics and object dynamics are *unknown*, an online estimation strategy is indispensable. A few unique challenges arise in parameter estimation in pHRI: (i) the human is usually unaware of the required motion for identification, (ii) the robot solely executing the identification-relevant motion may cause undesired human wrenches and may disturb the human partner [4], (iii) the desired estimation strategy needs to account for the human presence by simultaneously allowing the human partner to perform a desired motion *while* inducing an identification-relevant motion, necessary for parameter convergence. This work presents an approach achieving the estimation of the unknown parameters, while avoiding undesired human interaction wrenches, thus enabling the human to perform a motion.

II. MODELING THE HUMAN-ROBOT MANIPULATION TASKS

We consider a task where a human and a robot cooperatively manipulate a rigid object in $SE(3)$ with unknown relative kinematics and object dynamics as depicted in Fig. 1. Coordinate frames of the human, robot, and object are denoted with $\{h\}$, $\{r\}$, and $\{o\}$, respectively. The object frame coincides with the object's center of mass. All coordinate frames are fixed. The pose is represented by $\boldsymbol{x}_i = [\boldsymbol{p}_i^T, \boldsymbol{q}_i^T]^T \in SE(3)\ \forall i \in h, r, o$ containing the translation $\boldsymbol{p}_i \in \mathbb{R}^3$, and orientation $\boldsymbol{q}_i \in S^3$ represented by a unit quaternion. Let $\dot{\boldsymbol{x}}_i = [\boldsymbol{v}_i^T, \boldsymbol{\omega}_i^T]^T \in se(3)$ be a twist vector containing the translational $\boldsymbol{v}_i \in \mathbb{R}^3$, and angular velocity $\boldsymbol{\omega}_i \in \mathbb{R}^3$, and let $\ddot{\boldsymbol{x}}_i = [\dot{\boldsymbol{v}}_i^T, \dot{\boldsymbol{\omega}}_i^T]^T$ contain translational and angular accelerations. Each agent applies wrench $\boldsymbol{u}_i = [\boldsymbol{f}_i^T, \boldsymbol{t}_i^T]^T \in \mathbb{R}^6$ with $\boldsymbol{f}_i \in \mathbb{R}^3$ as the force and $\boldsymbol{t}_i \in \mathbb{R}^3$ as the torque applied at the grasping point.

Inconsistent robot motion, i.e. robot motion not matching the human motion, causes undesired interaction wrenches, which disturb the human during interaction. A common human dynamics model suggests that the human applies a wrench $\boldsymbol{u}_h$ when there is a difference between the desired and the actual human motion, expressed, as an example, as

$$\boldsymbol{K}_h(\boldsymbol{x}_h^d - \boldsymbol{x}_h) = \boldsymbol{u}_h \tag{1}$$

with $\boldsymbol{x}_h^d$ and $\boldsymbol{x}_h$ as the desired and actual human motion, and $\boldsymbol{K}_h \in \mathbb{R}^{6\times 6}$ as the translational and rotational stiffness of the human wrist. From (1) it can be inferred that zero human wrench, i.e. $\boldsymbol{u}_h = 0$, indicates a zero difference between the desired and actual human pose, i.e. $\boldsymbol{x}_h^d = \boldsymbol{x}_h$.

In order to estimate the unknown parameters (any of the parameters in Fig. 1), the object motions need to be sufficiently exciting [6]. Performing such motion may cause undesired human interaction wrenches (1) and may disturb the human when performing a desired motion. We aim at performing

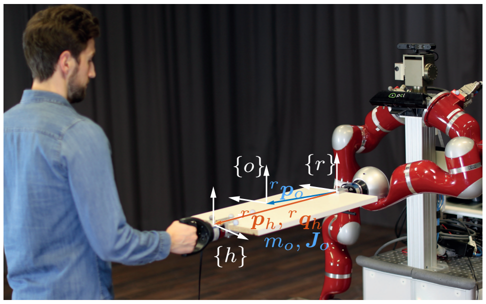

Fig. 1: Cooperative human-robot object manipulation task: Relative kinematics is parametrized with the displacement ${}^r\boldsymbol{p}_h$, and orientation ${}^r\boldsymbol{q}_h$ (orange); Object dynamics with the mass m_o, center of mass ${}^r\boldsymbol{p}_o$, and inertia matrix $\boldsymbol{J}_o$ (blue).

The research leading to these results has received funding from the European Union Seventh Framework Programme FP7/2007-2013 under grant agreement n° 601165 of the project "WEARHAP - WEARable HAPtics for humans and robots".

D. Ćehajić, P. Budde gen. Dohmann, and S. Hirche are with the Chair of Information-oriented Control, Technical University of Munich, Germany. `{denis.cehajic, pablo.dohmann, hirche}@tum.de`

identification-relevant motions, such that the difference to the human desired motion is minimal, according to (1), as

$$\min_{x_r} ||\boldsymbol{u}_h||^2 \ . \tag{2}$$

III. AVOIDING UNDESIRED HUMAN WRENCHES

We derive an appropriate robot motion inducing identification-relevant motions and avoiding undesired human interaction wrenches. During interaction the human and the robot do not necessarily apply wrenches along all directions. Let $\bar{\boldsymbol{u}}_i \in \mathbb{R}^{n_i}$ denote applied wrenches of a partner, with n_i as the partner's input dimensionality. Let ${}^h\bar{\boldsymbol{G}}_r \in \mathbb{R}^{n_h \times n_r}$ denote the partial grasp matrix relating human and robot applied wrenches. In the following, we present a strategy for the case $n_h < n_r$, i.e. when the robot has greater input dimensionality than the human.

The internal wrench component results in no motion and it lies in the null space of ${}^h\bar{\boldsymbol{G}}_r$ [7]

$$\text{null}({}^h\bar{\boldsymbol{G}}_r) = \{\bar{\boldsymbol{u}}_r | {}^h\bar{\boldsymbol{G}}_r \bar{\boldsymbol{u}}_r = 0\} \ . \tag{3}$$

from which it can be inferred that minimal disturbance of (1) is achieved if the identification-relevant motions lie in the null space of ${}^h\bar{\boldsymbol{G}}_r$. This means that the non-redundant directions can be chosen for inducing an identification-relevant motion achieving (2).

Let $\dot{\boldsymbol{x}}_r^d$ denote the robot motion necessary for tracking a human desired motion and inducing an identification-relevant motion satisfying the persistent excitation condition [6], and $\dot{\bar{\boldsymbol{x}}}_\text{id} \in \mathbb{R}^{n_r - n_h}$ as the motions in the directions not spanned by the human motion along the redundant directions $\dot{\boldsymbol{x}}_h^R \in \mathbb{R}^{n_h}$. Motions $\dot{\bar{\boldsymbol{x}}}_\text{id}$ are induced by

$$\begin{aligned} \dot{\boldsymbol{x}}_r^d =& ({}^h\bar{\boldsymbol{G}}_r^T)^+ \dot{\boldsymbol{x}}_h^R \\ &+ (\boldsymbol{N}(\boldsymbol{I}_{n_r} - ({}^h\bar{\boldsymbol{G}}_r^T)^{+\,h}\bar{\boldsymbol{G}}_r^T))^+ (\dot{\bar{\boldsymbol{x}}}_\text{id} - \boldsymbol{N}({}^h\bar{\boldsymbol{G}}_r^T)^+ \dot{\boldsymbol{x}}_h^R) \ , \end{aligned} \tag{4}$$

where $({}^h\bar{\boldsymbol{G}}_r^T)^+ \dot{\boldsymbol{x}}_h^R$ is responsible for tracking a desired human motion along the redundant directions, and the rest of the expression induces an identification motion $\dot{\bar{\boldsymbol{x}}}_\text{id}$, in the null space of ${}^h\bar{\boldsymbol{G}}_r$, $\boldsymbol{N} \in \mathbb{R}^{(n_r - n_h) \times n_r}$ contains non-redundant rows of the partial grasp matrix.

IV. EVALUATION

Description: We conducted a small user study to evaluate the effect of the induced identification motions during a human motion. The setting consists of a human partner grasping a handle, a 7 DoF robotic manipulator and a rigid object (as in Fig. 1). Wrenches of both the human and the robot are measured by the 6 DoF JR3 force/torque sensors. We analyze the performance with 5 human participants, who are instructed to move 0.5 m along the negative y-direction. The human velocity is estimated using the Kalman filter from the human position, acquired by the motion tracking system. We evaluate: (i) the proposed approach (4), (ii) a *naive* approach by simply adding the equivalent robot and identification motions, i.e. $\dot{\boldsymbol{x}}_{r,\text{naive}} = \dot{\boldsymbol{x}}_r + \dot{\boldsymbol{x}}_\text{id}$, and (iii) when no motion is introduced ($\dot{\boldsymbol{x}}_\text{id} = \boldsymbol{0}_{6\times1}$), i.e. following the desired human motion, such to compare the effects of (i) and (ii). Each condition is repeated 20 times, totaling in 60 trials per subject; the order of all trials is randomized. The induced motion is $\dot{\boldsymbol{x}}_\text{id} = [\boldsymbol{0}_{3\times1}, (\boldsymbol{\omega}_\text{id})^T]^T$, where $\boldsymbol{\omega}_\text{id} = \frac{\boldsymbol{A}^d}{2} - \boldsymbol{A}^d\text{step}(\boldsymbol{F}^d)$ (rad/s), with the amplitude $\boldsymbol{A}^d = [0.2, 0.15, 0.1]^T$ and the frequency $\boldsymbol{F}^d = [0.33, 0.71, 0.5]^T$.

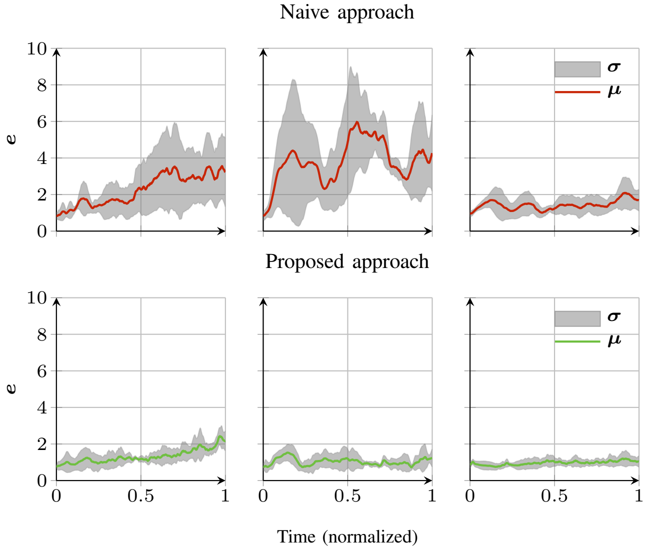

Fig. 2: Interaction error averaged over all trials and subjects: (left to right) mean $\boldsymbol{\mu}$ and variance $\boldsymbol{\sigma}$ along components $f_{h,x}, f_{h,y}, f_{h,z}$, for the naive (top) and proposed (bottom).

Results: To isolate the effect of undesired interaction we define the interaction error as $\boldsymbol{e}(t) = \frac{|\boldsymbol{f}_i(t) - \boldsymbol{\mu}_\text{ref}|}{\boldsymbol{\sigma}_\text{ref}}$, $\forall i = 1, 2$, where $\boldsymbol{f}_i$ are the human interaction forces of the proposed and naive interaction, respectively, and $\boldsymbol{\mu}_\text{ref}$, $\boldsymbol{\sigma}_\text{ref}$ are the mean and standard deviation of the reference force $\boldsymbol{f}_\text{ref}$ over all trials for a single subject. The error is weighted with the confidence in the desired force, represented by $\boldsymbol{\sigma}_\text{ref}$. The resulting interaction error $\boldsymbol{e}$ is then averaged over all trials for each subject. The averaged interaction errors are depicted in Fig. 2. It is evident that the proposed approach reduces the interaction error exerted to the human partner: the mean is $[1.3, 1.0, 1.0]^T$ and the maximum error is $[2.4, 1.5, 1.2]^T$ using the proposed approach, compared to $[2.3, 3.8, 1.4]^T$ as the mean and $[3.6, 6.0, 2.1]^T$ as the maximum error using the naive approach. The proposed approach shows a drastic improvement in terms of interaction error.

REFERENCES

[1] M. Lawitzky, A. Moertl, and S. Hirche, "Load sharing in human-robot cooperative manipulation," in *Robot and Human Interactive Communication (RO-MAN), 19th IEEE International Symposium on*, 2010, pp. 185–191.

[2] A. Moertl, M. Lawitzky, A. Kucukyilmaz, M. Sezgin, C. Basdogan, and S. Hirche, "The role of roles: Physical cooperation between humans and robots," *Int. J. of Robotics Research*, vol. 31, pp. 1657–1675, 2012.

[3] A. Bussy, A. Kheddar, A. Crosnier, and F. Keith, "Human-humanoid haptic joint object transportation case study," in *2012 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS)*, 2012, pp. 3633–3638.

[4] D. Cehajic, S. Erhart, and S. Hirche, "Grasp pose estimation in human-robot manipulation tasks using wearable motion sensors," in *IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, 2015, pp. 1031–1036.

[5] D. Cehajic, P. gen. Dohmann, and S. Hirche, "Estimating unknown object dynamics in human-robot manipulation tasks," in *IEEE Int. Conf. on Robotics and Automation*, 2017.

[6] K. J. Astrom and B. Wittenmark, *Adaptive Control*, 2nd ed. Addison-Wesley Longman Publishing Co., Inc., 1994.

[7] B. Siciliano and O. Khatib, *Springer Handbook of Robotics*. Springer Science & Business Media, 2008.