A Minimum Invasive Strategy to Guarantee Safety Under Unexpected Unintentional Human-Robot Contact*

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Abstract— **The problem of designing an active robot reaction scheme to increase safety against unexpected, unintentional robot contacts with a human or its environment, is considered in this work. Its main functionalities are a) the regulation of the interaction force profile within acceptable/safe boundaries and b) the prevention of undesirable after-contact collisions. The developed methodology is model-free and operates at the high level of reference trajectory determination, producing bounded and sufficiently smooth modifications of the nominal reference, leaving intact the embedded low-level, robot position controller. It is underlined that the proposed minimal invasive solution, is evaluated via experiments performed on a KUKA LWR4+ robotic manipulator equipped with a Shadow Hand-Lite having optoforce sensors attached at its fingertips.**

I. INTRODUCTION

In the last two decades the idea of human-robot collaboration and symbiosis has been taken forward, with humans taking advantage of robotic skills such as high computation capabilities, data processing, movement precision etc. Robots get guided by humans on how to use their skills and learn to efficiently deliver a process. Within this concept, industrial and service robots have been used in several applications.

Service robots aim to support humans with every-day tasks delivering services that include tasks, in common space or even in collaboration. To guarantee safe human-robot coexistence or even collaboration, very strict safety rules need to be established to avoid potential unintentional contact. Concurrently, the use of industrial robots has also increased with the need for more human-robot collaboration and cooperation. New products have short lifecycles requiring quick changes and build-in flexibility in production lines. Robots can deliver a wide variety of processes and impose flexibility, however operating within a structured isolated environment can limit their abilities and potential benefit from human-robot interaction. Therefore, recent efforts have focused on human-robot interaction that requires extended collaboration in a common workspace, while guaranteeing human safety.

Regardless the area of application, human-robot collaboration infers the same danger of harmful situations from unintentional contact and several methods have been developed. These can be roughly divided into passive and active methods. Passive methods comprise approaches where safety is embedded into the robot design to avoid harmful situations even if an unintentional contact occurs [1][2][3]. On the contrary, active approaches aim to handle the robot in such a way that the contact will be avoided or will have the least possible impact. This is done by actively intervening rather than passively responding to an upcoming contact.

Active methods are classified into contact prevention and contact reaction. The former, aim at identifying upcoming contacts and react towards their prevention or if unavoidable, to minimize harmful consequences [4][5]. The latter, intervene directly to the low-level robot control, to establish a safe reaction strategy. In this direction, the first approach suggested in [6], where mechanisms ranging from immediate stop and switching into gravity compensation to the more sophisticated motor and link inertia regulation, with the robot moving towards the opposite to the contact force direction with a derivable velocity defined via an admittance control scheme, were proposed.

In this work, our attention is concentrated to unexpected, unintentional contacts of the robot with a human or its environment. Therefore by definition, the robot is unable to predict the appearance of the unintentional contact, constituting contact reaction philosophy as the natural working framework. More recently in [7], a passivity model-based controller is designed to guarantee on one hand nominal motion quality and on the other, compliant reaction to unintentional contact. Interestingly, discontinuities between the two modes of operation were carefully avoided. However, when the contact force vanishes, the robot returns to its nominal operation, increasing the risk of repeated collisions, especially when the source of initial contact is still forming an obstacle to the nominal robot motion. Another approach presented in [8], defines different strategies for intentional and unintentional contact, based on a force threshold. When unintentional contact is detected, the robot is accelerated towards an opposite to contact direction before it freezes. The method shows a quick response on contact however, similar to [7], it generates significant after contact motion increasing the probability of additional unintentional contacts.

Exploiting the logical assumptions that the embedded robot position controller is designed to accurately track any given, bounded and sufficiently smooth reference trajectory, modifications of the closed-loop scheme are proposed in this paper that apply at the higher level of reference trajectory determination, leaving intact the build-in robot position controller. The propose scheme, called reference-shaping is comprised of a Contact Detection module, which i) decides

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on the presence of a contact, based on the availability of either force/torque measuring devices or reliable force estimation mechanisms and ii) provides the direction of compliance. The architecture is completed by a Re-shaping unit and a Reference Trajectory Generation unit. The latter is responsible for producing a bounded and sufficiently smooth modification of the nominal reference trajectory signal; thus achieving compatibility with the embedded robot position controller. The former, generates the necessary driving signals that enable the proper functionality of the Reference Trajectory Generator. In addition, the proposed architecture is model-free, thus formulating, in total, a minimal invasive solution. The basic functional properties of the developed scheme are a) the regulation of the interaction force profile within acceptable/safe boundaries and b) the prevention of undesirable after-contact collisions.

The rest of the paper is organized as follows. In section II the problem is stated. In section III, the proposed solution is presented and analyzed. Evaluation results based on real experimentation performed with the help of a KUKA LWR4+ robotic manipulator equipped with a Shadow Hand-Lite having an optoforce sensor, attached at its fingertips, are obtained in section IV. Conclusions are stated in section V.

II. Problem Statement

Consider an n-DoF revolute joint robotic manipulator with $q \in \mathbb{R}^n$ denoting the joint position vector and $s \in \mathbb{R}^3$, $r \in SO(3)$ describing the position and orientation respectively of the end-effector with respect to the inertia frame. Moreover, let $p \triangleq [s^T \ \varphi_r^T]^T$ with φ_r being the orientation parameters e.g., Euler angles. Denoting with $J_a(q)$ and $J(q)$ the analytical and the robot Jacobian respectively then $\dot{p} = J_a(q)\dot{q}$ and $U = J(q)\dot{q}$ with $U \triangleq [\dot{s}^T \ w^T]^T \in \mathbb{R}^6$ being the end-effector generalized velocity. Assuming a non-redundant manipulator operating away from singularities, the operational space robot dynamics are:

$$M(p)\ddot{p} + C(p,\dot{p})\dot{p} + G(p) + W(p)F = u, \qquad (1)$$

with

$$\begin{aligned} M(p) &= [J_a(q)H^{-1}(q)J_a^T(q)]^{-1}, \\ C(p,\dot{p}) &= J_a^{-T}(q)C_o(q,\dot{q})\dot{q} - M(p)\dot{J}_a(q)\dot{q}, \\ G(p) &= J_a^{-T}(q)G_o(q), \\ W(p) &= J_a^{-T}(q)J^T(q), \\ u &= J_a^{-T}(q)\tau. \end{aligned}$$

In the aforementioned expressions $H(q)$ denotes the positive definite robot inertia matrix, $C_o(q,\dot{q})\dot{q}$ is the Coriolis and centripetal force, $G_o(q)$ is the gravity force vector, τ is the joint input vector and $F \in \mathbb{R}^6$ represent external disturbances typically owing (in this work) to the unintentional unforeseen, contacts of the robotic arms with a human or the environment. To increase clarity of presentation, in what follows our attention is restricted to the non-redundant position tracking problem. However, despite the simplification introduced, the generality of the main idea is maintained. To proceed, notice that in this case the W-matrix appearing in (1) becomes $W = I_3$ where I_3 is the 3x3 identity matrix. It is further assumed that the robot is equipped with a state-feedback position controller capable of driving the end-effector position s to accurately follow a given, bounded, and C^1 trajectory $s_n(t)$.

Control Objectives: Keeping unaltered the embedded robot position controller and for a given range of admissible robot speeds, the objective of this work is to provide all modifications necessary on the closed-loop system such that in case of an unexpected, unintentional contact with a human or the environment: O_1) The interaction force profile is regulated within acceptable/safe boundaries, and O_2) additional, after-contact collisions are prevented.

Remark 1: To guarantee safe interaction with humans, the robotic system has to be a compliant in case of unexpected, unintentional contacts. In this way, the maximum interaction force experienced can be restricted to acceptably low (safe) values and the contact duration can be reduced (satisfaction of O_1). Nevertheless, compliance should be performed with caution, as a high-compliant robot will on one hand lead to practical interaction force minimization, but on the other, will generate significant after-contact motion, which magnifies the probability of after-contact collisions (violation of O_2)

Remark 2: As clarified in Remark 1, the candidate solution (closed-loop modification) represents a viable compromise between O_1 and O_2. Additionally, such a solution should be i) compatible with the embedded robot position controller, which is assumed fixed and ii) of low analytic and computational complexity to enhance fast/immediate reaction to unexpected, unintentional contacts.

III. Proposed Solution

Following the presentation of section II, the main idea of the proposed solution builds on the concept of reference shaping, which is illustrated in Fig 1.

The robot is operated with its embedded (fixed) position controller designed to accurately track a bounded and C^1 reference trajectory $s_n(t)$. Upon an unexpected, unintentional contact with a human or its environments, the developed interaction force F is first detected and consequently transfered to the re-shaping module, whose objective is the on-the-fly modification of $s_n(t)$, to guarantee, if precisely followed, the quality of compliance via the achievement of both O_1 and O_2. In this direction, the developed modifications should preserve the boundedness and C^1 attributes of $s_n(t)$ to maintain the compatibility between the produced reference trajectory and the low-level robot position controller.

In what follows the main modules comprising reference shaping are presented and analyzed.

Contact Detection: In unexpected, unintentional contacts, reaction time is critical. In that respect, contact detection should be computationally simple and avoid the introduction of additional time-delays in the closed-loop system. In that respect, let f_{th} denote a predefined threshold value; contact is assumed provided that the i-th element of the measured

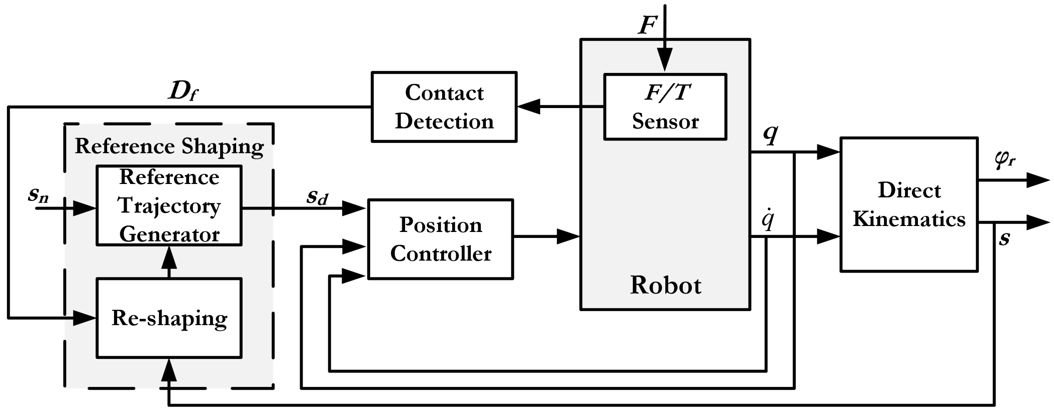

Fig. 1. The concept of reference shaping

interaction force norm exceeds the given threshold i.e., $|F_i(t)| \geq f_{th}$. In such a case, the output of the Contact Detection Module is the actual interaction force, otherwise, it admits a zero value. Contact Detection can be easily implemented with the help of a dead-zone function:

$$D_{f_i} = \begin{cases} 0 & \text{, if } |F_i(t)| < f_{th}, i = 1,2,3 \\ F_i(t) & \text{, if } |F_i(t)| \geq f_{th} \end{cases} \tag{2}$$

where with D_{f_i}, the i-th output of the Contact Detection Module is denoted.

Remark 3: The actual threshold value f_{th} utilized in (2) affects directly the sensitivity of the whole reference shaping scheme, and in that respect it should be carefully selected. If very low values are admitted, noise could be erroneously perceived as a contact force signal, thus giving rise to false-alarms and spurious robotic motions. On the other hand, increased values of f_{th} tend to produce large interaction forces, jeopardizing the satisfaction of O_1. In this direction, the sensitivity of the force measuring device is also crucial.

Reference Shaping: The reference shaping module is comprised of two units (Reference Trajectory Generator, Re-shaping) in series connection as illustrated in Fig. 2.

The *Reference Trajectory Generator* unit is responsible for producing a bounded and at least C^1 modification of the nominal reference trajectory signal, compatible with the embedded robot position controller. The *Re-shaping* unit produces the driving signals that enable the proper functionality of the Reference Trajectory Generator unit.

Let t_c denoting the time of contact detection; the analytical expression implementing the reference shaping module are:

$$s_{d_i}(t) = s_{n_i}(t) + I_{f_i}(z_i)(x_i(t) - s_{n_i}(t)), \; i = 1,2,3 \tag{3}$$

$$\dot{x}_i = \frac{1}{k_i} D_{f_i}, \qquad x_i(t_c) = s_{n_i}(t_c), \qquad i = 1,2,3 \tag{4}$$

$$\dot{z}_i = k_{o_i} |D_{f_i}|, \qquad z_i(0) = 0, \qquad i = 1,2,3 \tag{5}$$

where I_{f_i} is a continuously differentiable switching function with

$$I_{f_i} : [0, \delta] \to [0, 1], \quad I_{f_i} : (\delta, \infty) \to 1, \tag{6}$$

and

$$I_{f_i}(0) = 0, \quad \frac{dI_{f_i}(0)}{dz_i} = 0, \quad \frac{dI_{f_i}(\delta)}{dz_i} = 0, \tag{7}$$

$$\frac{dI_{f_i}}{dz_i} > 0, \quad \forall \; z_i \in (0, \delta), \tag{8}$$

$$\frac{d^2 I_{f_i}}{dz_i^2} > 0, \quad \forall \; z_i \in (0, \delta/2), \tag{9}$$

$$\frac{d^2 I_{f_i}}{dz_i^2} < 0, \quad \forall \; z_i \in (\delta/2, \delta), \tag{10}$$

In (6) - (10) , δ is a strictly positive design constant. Regarding the implementation of I_{f_i}, $i = 1,2,3$ standard polynomial functions can be utilized.

Corollary 1 (s_d - position control compatibility): For a given range of admissible robot speeds, the produced by the reference shaping module, modified reference trajectory $s_d(t)$ is bounded and C^1.

Proof: Under the logical assumption that the robot position controller is designed to accurately follow any bounded and C^1 reference trajectory, s_d - position control compatibility is guaranteed by showing that (2) - (10) introduce a bounded and C^1 modification of the original nominal reference trajectory $s_n(t)$. In that direction, notice that owing to (2), (5) and (6) - (10) I_{f_i}, $i = 1,2,3$ are bounded and C^1. The same properties hold for $x_i(t)$, $i = 1,2,3$ owing to (2) and (4). Hence, as $s_{n_i}(t)$, $i = 1,2,3$ are bounded and C^1 by construction, the incorporation of (3) yields directly the boundedness and C^1 properties of the modified reference trajectory $s_{d_i}(t)$, $i = 1,2,3$.

The rationale of proposing (2) - (10) is the following: Upon detection of an unintentional contact, the nominal reference trajectory $s_n(t)$ is first canceled, via the functionality of I_{f_i} in (3) and concurrently a new reference $s_d(t)$ is enforced as determined by (3) and (4). It is stressed that owing to (2) - (4), the direction of $s_d(t)$ is along the direction of the interaction force $F(t)$, thus introducing the

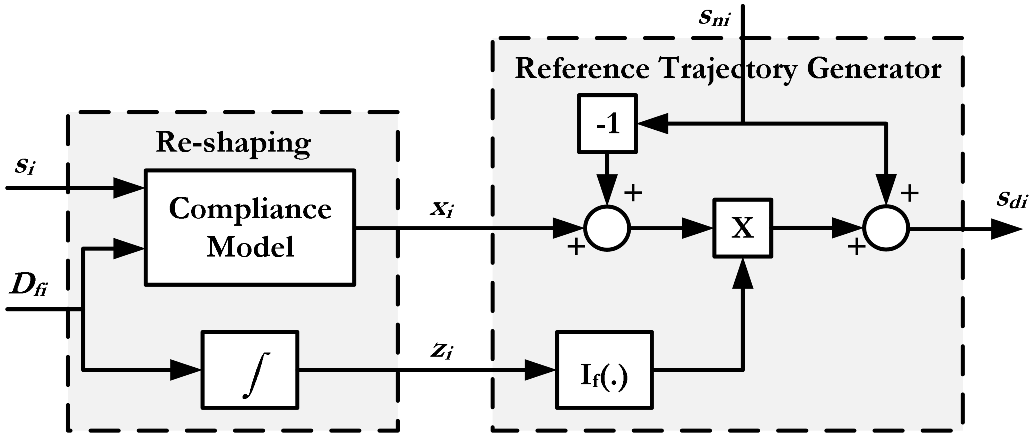

Fig. 2. The Block diagram of the i-th element of the reference shaping module

desirable compliant behaviour. Notice, further that owing to Corollary 1, the transition from $s_n(t)$ to $s_d(t)$ is bounded and sufficiently smooth (i.e., C^1). When the interaction force drops below f_{th}, D_{f_n} from (2) becomes zero that in turn sets to zero the desirable motion speed as dictated by (4), in which case, the robot is expected to maintain its current position, until a new task (a new reference trajectory) is downloaded from the robot's motion planer. The latter behaviour is imposed via (5), which essentially operates as a latch, preventing z_i from admitting the zero value. In that respect, if the robot position controller is designed to achieve accurate tracking of a bounded and at least C^1 reference trajectory, the above described modification on the reference signal introduces a compliant robot motion in the direction of the interaction force, until that force becomes practically zero, where it stops moving waiting for a new command i.e., a new reference trajectory.

Remark 4 (Control Objectives Satisfaction): It should be underlined that the regulation of the interaction force profile and the after contact motion (i.e., the fulfillment of the control objectives O_1 and O_2) are achieved via the appropriate selection of f_{th} and the strictly positive gains k_i, $i = 1, 2, 3$. Specifically for a fixed f_{th}-value, the $k_i{}'s$ should be selected following a task specific sensitivity analysis, as increased k_i-values tend to restrict the after contact motion (satisfaction of O_2), magnifying however, the maximum interaction force experienced leading to the possible violation of O_1. In addition, the complexity (analytic, computational) of the proposed modification (2)-(10) on the closed-loop system is clearly low, finalizing the discussion on the control objectives satisfaction.

Remark 5 (Minimum Invasive Solution): the proposed architecture is model-free and operates at the high control level of reference trajectory determination, leaving intact the embedded low-level robot's position controller. In that respect, the designed methodology constitutes a minimum invasive solution.

IV. Experimental Results

To evaluate the proposed safety under unexpected, unintentional contact reaction strategy, a number of experiments have been carried out, utilizing a KUKA LWR4+ robotic manipulator equipped with a Shadow Hand-Lite having optoforce sensors attached at its fingertips. The experimental hardware is visualized in Fig 3.

The robot's end-effector is initially at rest at position $P_0 = [-0.852, 0.094, 0.501]^T$, dictated to follow a nominal reference trajectory on the Y axis, towards position $P_1 = [-0.852, -0.1, 0.501]^T$ based on the fifth order polynomial $s_n(t) = 0.094 - 0.194(10(t/d)^3 - 15(t/d)^4 + 6(t/d)^5)$, where d is the movement duration according to the desired contact velocity. The robot comes in contact with its environment via it's optoforce sensors. To increase safety against unexpected, unintentional contacts, the strategy determined by (2) - (10) is utilized. Exploiting the fact that optoforce sensors produce very clean and of high resolution force measurements, the threshold value in (2) is set as low as $f_{th} = 0.5N$. Moreover, the switching function I_{f_i} is implemented as a fifth order polynomial:

$$I_{f_i}(z_i) = 10(z_i/\delta)^3 - 15(z_i/\delta)^4 + 6(z_i/\delta)^5 \tag{11}$$

with $\delta = 1$.

As stated in Remark 4, to determine vales for the strictly positive gains $k_i, k_{o_i}, i = 1, 2, 3$ appearing in (4) and (5) respectively, a sensitivity analysis procedure is followed. Specifically, the robot is moving with velocity $0.1m/s$ when it comes in unintentional contact with a flat wooden surface along its normal direction[1]. The experiment is repeated for different values of the k-parameter keeping k_o fixed at $k_o = 50$. Both the maximum contact force and the after contact displacement experienced when the proposed safety mechanism is incorporated, are recorded. Consequently, the robot mean velocity is increased to $0.2m/s$ and the procedure

[1]In this scenario, the reference trajectory is modified only along the normal direction and therefore only a single parameter k and k_o have to be determined

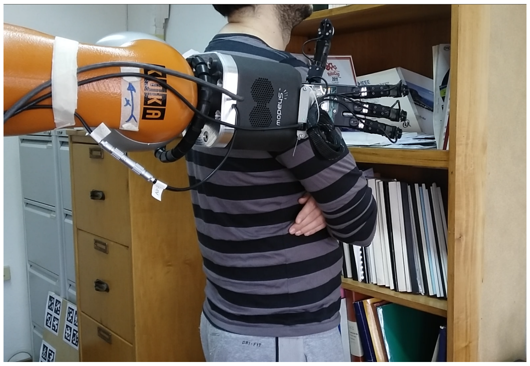

Fig. 3. Experimental set-up during Human-Robot contact

is repeated. The results are plotted in Fig 4. Evidently, reducing k tends to minimizing the maximum contact force on the one hand, which is desirable, but on the other, increases the after contact displacement, increasing in this way the probability of after contact collision. Apparently, a very good compromise is achieved for $k = 50$. The experiment is repeated but now the k-parameter is kept fixed at its best obtained value ($k = 50$), while k_o is varied. The results are provided in Fig 5. It is observed that the reduction of k_o affects negatively both the maximum contact force and the maximum after contact displacement, with the almost optimal value being $k_o = 50$.

Concluding, the aforementioned sensitivity analysis procedure resulted in $k = k_o = 50$. These parameter values are also utilized to evaluate the proposed safety mechanism under unexpected, unintentional contact with a human. The contact force profile is pictured in Fig 6 for contact velocities $0.1m/s$ and $0.3m/s$. Apparently, the maximum after contact forces experienced are kept low, not exceeding $0,76N$ and $1.64N$ in any direction at $0.1m/s$ and $0.3m/s$ respectively. The maximum after contact displacements recorded are $0.0107m$ and $0.0221m$ for contact velocities $0.1m/s$ and $0.3m/s$ respectively.

V. CONCLUSIONS

An active robot reaction scheme was proposed to efficiently handle unexpected, unintentional robot contacts with humans or its environment. The developed solution was shown to be minimally invasive as it reshapes only the reference trajectory, leaving unaffected the embedded, low-level, robot position controller. The main guaranteed functionalities are the regulation of the interaction force profile within safety boundaries and the prevention of the after-contact collisions. Experiments performed with the help of a KUKA LWR4+ robotic manipulator, equipped with a Shadow Hand-Lite having optoforce sensors at its fingertips were utilized to evaluate the proposed approach.

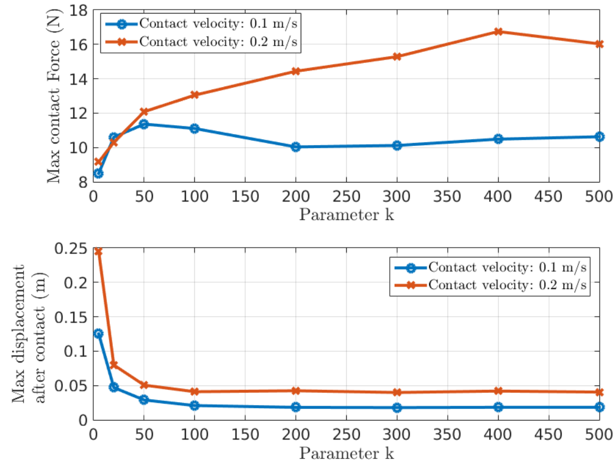

Fig. 4. Maximum contact force (upper plot) and maximum after contact displacement (lower plot) for contact velocity $V = 0.1\ m/s$ and $V = 0.2\ m/s$ while varying parameter k

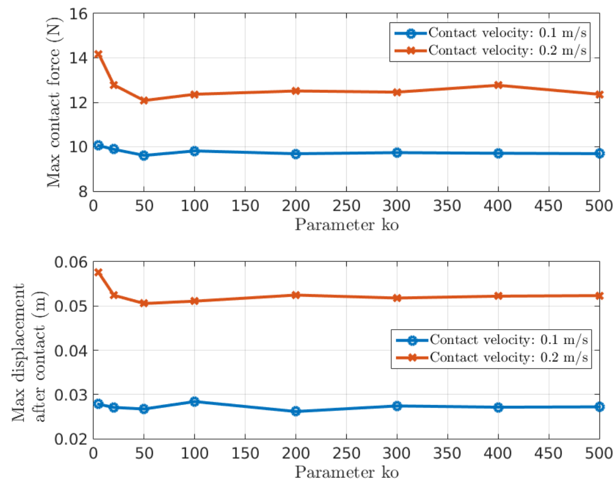

Fig. 5. Maximum contact force (upper plot) and maximum after contact displacement (lower plot) for contact velocity $V = 0.1\ m/s$ and $V = 0.2\ m/s$ while varying parameter k_o

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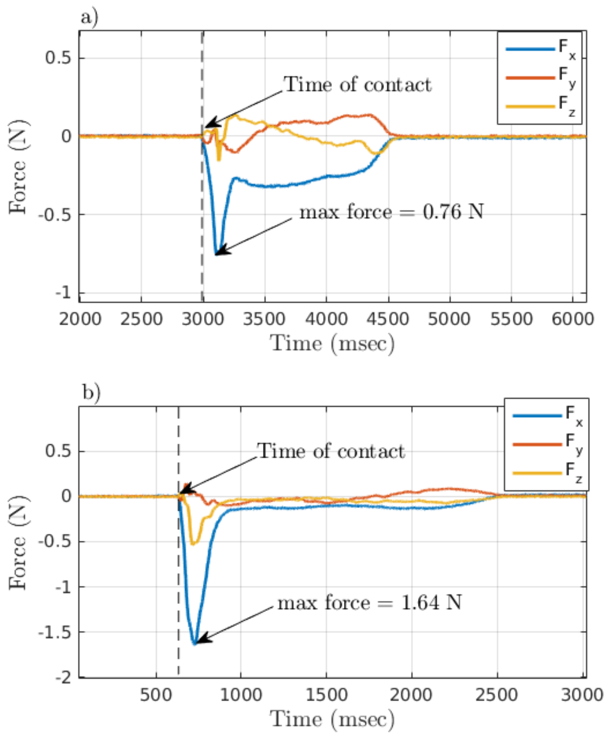

Fig. 6. Human-robot contact force profile when contact velocity is a) $V = 0.1\ m/s$ and b) $V = 0.3\ m/s$

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