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Force-tracking impedance control for manipulators mounted on compliant bases

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***Abstract*— The paper presents a control law for interaction tasks with environments of unknown geometrical and mechanical properties by manipulators mounted on compliant bases. Based on force-tracking impedance controls, the control strategy allows the execution of such class of tasks using the estimation of base position as a feedback in the control loop, requiring at the same time the on-line estimation of the environment stiffness. The properties of the control using non co-located sensors and the dynamic configuration of the coupled base-robot-environment system are studied. An Extended Kalman Filter is used for the estimation of the environment because of measurement uncertainties and errors in compound interaction model. The base is modelled as a second-order physical system with known parameters (offline identification before the task execution) and the base position is estimated from the measure of interaction forces. The grounding position estimation and the defined control law are validated in simulation and with experiments, especially dedicated to an insertion-assembly task. Control laws with and without the base compensation in the feedback loop are compared, verifying the effectiveness of the developed control law.**

I. Introduction

Explicit force or deformation reference cannot be directly obtained in impedance control, undermining the suitability of impedance control in those technological tasks that require some degree of process control over the interaction. Many efforts have been, in fact, made to achieve a force/position tracking with impedance control despite the lack of knowledge of the environmental stiffness and location. Primarily, force-tracking impedance control involves the generation of a reference motion as a function of the force error [1], [2], under the condition that the environment stiffness is variously unknown, *i.e.* estimated as a function of the measured force. Dynamical properties of interacting environments can be loosely predictable to a vast class of useful conditions [3]. When robot manipulators are mounted on compliant bases, however, the base deformation can significantly influence the interaction accuracy in a wide critical bandwith [4], including contacts transients. The base elasticity is, in fact, remarkably crucial from a stability point of view due to the presence of robot-base coupled dynamics. This is variuously the case of flexible-structure-mounted manipulators, macro-mini manipulation systems, free-floating or mobile-platform mounted manipulators, which are very relevant cases of robots used in naval, aerial, hazardous (nuclear, chemical) remoted applications or typical industrial moving-base mounting (*e.g.* cranes, rails).

In such cases, the coupled dynamics with internal forces depends on both mechanical (mass, damping and stiffness properties of the base and the robot control) and kinematics configuration (instantaneous trajectory, pose in the workspace) conditions. Some works are dedicated to assign explicit values to such relationship in the case of gravitation-free application [5], where motion trajectories are planned along minimum-energy configurations of a Coupling Map, or in the case of standard gravitation load in order to highlight the influence of single terms on the coupled-system dynamics [6]. More research has been instead dedicated to model-based control, focusing on the accurate position control in noncontact operations using inertial damping [7], [8], [9] or two-time scale controllers (fast joint torque control and slow vibration damping from the base motion/stiffness feedback) [10], [11]. Similar explicit/feedback approaches have also been extended to interaction tasks [12], [13] Impedance controllers considering known [14] or bounded [15] base stiffness in order to retune the actual manipulator stiffness to the desired one are extendedly investigated in terms of passivity for the case of quasi-static gravity load [14] and robustness/stability of control [15] also in case of contact bandwidth.

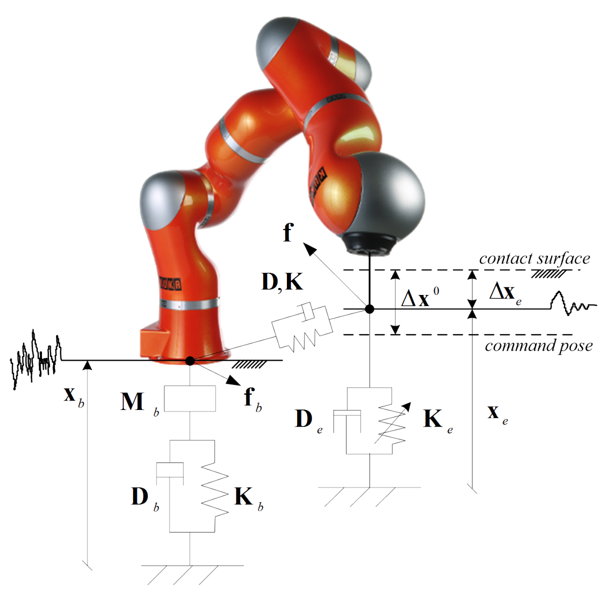

Fig. 1: Model and notation of an impedace-controlled manipulator interacting with the environment $()_e$ and mounted on a compliant base $()_b$.

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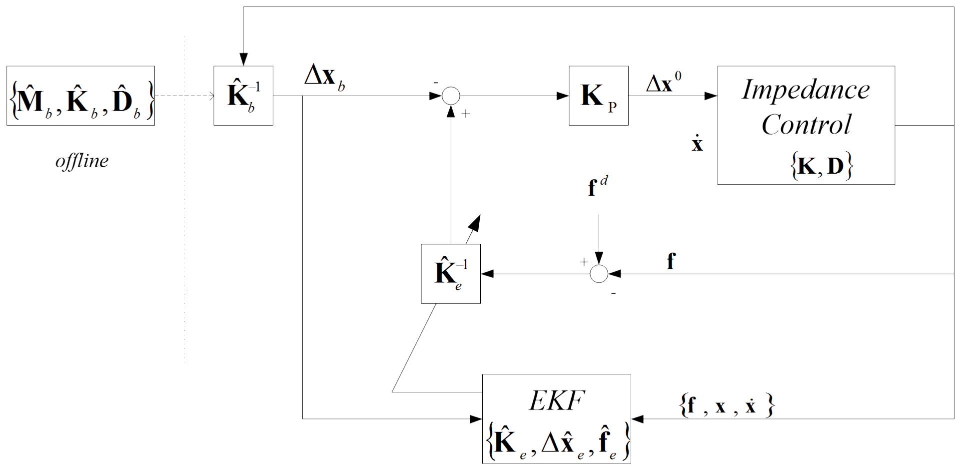


Fig. 2: Control flow-chart for a force-tracking ($\mathbf{f}^d$) application. Offline identification of base paramaters (left) provide online estimation of base deformation ($\Delta\mathbf{x}_b$) to be compensated.

In this paper we consider interaction tasks performed in impedance control with a required degree of force control along some of task directions. It is therefore required (i) to compensate for any deformation of the base derived from the robot dynamics and the contact-interaction dynamics, (ii) estimating the base deformation and the environment dynamical properties in order (iii) to set a pose reference for the impedance controller. While the environment estimation through an Extended Kalman Filter (EKF) has been already presented [16] for assembly tasks, the elastic response of the base in the closed-loop requires either a measurement or an estimation of its deformation. In the case of flexible-structure mounted manipulators, suitable sensor-based configurations are limited to embedded inertial units because of practical considerations. Alternatively, measurements of the base can be also replaced by an indrect estimation from the end-effector contact forces. In this case, however, tip forces propagating at the manipulator base could be negatively affected by the sensibility and accuracy of the measures themselves and by the dynamical model of the manipulator (*i.e.* the control) coupling the tip-base forces.

We therefore consider here a model-base estimation of the base displacement using a regular offline model identification for the base dynamical parameters and an online estimator whose filter parameters can be tuned according to the base and environment behavior. The estimation of the base displacement resulting from an interaction force-tracking task is evaluated with an absolute position sensor and the force-tracking performances evaluated in terms of force step change response during the task execution. The following sections are dedicated to the formulation of the coupled-system dynamics and the analysis of the effects of model parameters on the system behavior in order to suitable design both the control law and the estimators.

II. PROBLEM FORMULATION AND CONTROL MODEL

The compliant-base mounted robot problem is formulated considering simplified linear models for the base dynamics, neglecting nonlinearities (*e.g.* nonlinear stiffness, backlashes). The environment model is assumed to be loosely damped, with time-variant stiffness, as in many cases of unknown environments (models and notation in Fig. 1). For the purpose of simulation and system analysis, the environment stiffness $\mathbf{K}_e$ is considered constant, while in experiments it is eventually variable and estimated as $\hat{\mathbf{K}}_e$.

The force-tracking impedance control (Fig. 2) is realized defining a contact force $\mathbf{f}^0$ pattern acting on the environment during the execution of the task, dynamically forwarded as a pose(-velocity) reference $\Delta\mathbf{x}^0$. The dynamics of the coupled base-robot-environment system applies quasi-statically in terms of deformations for ciritically damped elements. The resulting pose reference is therefore computed as a function of the globally interacting stiffnesses and the interaction force. The designed control law enables, in fact, the compensation of the base compliance during the execution of the task:

$$\Delta\mathbf{x}^0 = \mathbf{K}_p(\hat{\mathbf{K}}_e^{-1}\mathbf{e}_f - \hat{\mathbf{x}}_b) \quad (1)$$

$$\mathbf{e}_f = \mathbf{f}^0 - \mathbf{f} \quad (2)$$

$$\hat{\mathbf{K}}_e \leftarrow \hat{\mathbf{K}}_e(\mathbf{f}, \Delta\mathbf{x}_e, \hat{\mathbf{x}}_b) \quad (3)$$

$$\hat{\mathbf{x}}_b \leftarrow \hat{\mathbf{x}}_b(\hat{\mathbf{M}}_b, \hat{\mathbf{D}}_b, \hat{\mathbf{K}}_b) \quad (4)$$

where forces $\mathbf{f}$ are sampled at the robot TCP in position $\mathbf{x}$, $\mathbf{x}_e$ is the environment position and $\Delta\mathbf{x}_e$ is the nominal environment deformation that, unlike the case of rigid base, has to be compensated for the base deformation $\hat{\mathbf{x}}_b$. Clearly, $\mathbf{x}_e = \mathbf{x}$ holds when the robot and the environment are in contact. Dynamics parameters of the base $\hat{\mathbf{M}}_b, \hat{\mathbf{D}}_b, \hat{\mathbf{K}}_b$ are identified offline (see Fig. 2 and Section IV-A) and assumed to be constant along the execution of the task. The base compliance compensation is therefore two-fold: it recovers the dynamics response of the equivalent robot impedance behavior w.r.t. the environment (see equations (1)-(2)) and it enables the actual estimation of the environment stiffness that is mandatory for expressing the tracking of $\mathbf{f}^0$ as a motion term in the impedance model (see equations (1)-(3)) . The inner control loop (task space impedance in Fig. 2), in fact, is performed by the model-based control

$$\mathbf{D}\Delta\dot{\mathbf{x}} + \mathbf{K}\Delta\mathbf{x} = \mathbf{f} \tag{5}$$

of the lightweight manipulator at mid/fast rate $(1-5ms)$, synchronously with the estimation of $\hat{\mathbf{K}}_e$ [16]. The deformation term $\Delta\mathbf{x} = \mathbf{x} + \Delta\mathbf{x}^0$ is the difference between the actual robot pose and the desired one $\Delta\mathbf{x}^0$ as generated in (1).

Such Cartesian pure impedance behavior is obtained by the control law [17]:

$$\mathbf{u} = -\mathbf{J}(\mathbf{q})^T\mathbf{f} + \mathbf{g}(\mathbf{q}) \tag{6}$$

where $\mathbf{J}$ is the Jacobian matrix of the robot and $\mathbf{g}(\mathbf{q})$ is the gravitational term of the robot. The control variable in (6) provides the joint-decoupled [18] dynamics in the task space that allows the robot to be considered as a pure impedance as in (5) and, consequently, in (1)-(3). The designed outer control law in (1) is performed at slower rate $(10-50ms)$ in order to ensure the steady state of the environment observer, with reference pose update tuned by the $\mathbf{K}_p$ proportional gain on the force-tracking error.

A. Closed-loop Coupled-System Dynamics

The dynamics of the coupled system made by compliant base, controlled robot and forced environment is therefore defined as follow:

$$\begin{cases} \mathbf{D}(\dot{\mathbf{x}} + \Delta\dot{\mathbf{x}}^0) + \mathbf{K}(\mathbf{x} + \Delta\mathbf{x}^0) = \mathbf{f} \\ \mathbf{M}_b\ddot{\mathbf{x}}_b + \mathbf{D}_b\dot{\mathbf{x}}_b + \mathbf{K}_b\mathbf{x}_b = \mathbf{f}_b \\ \sum_i (\mathbf{D}_e^i\dot{\mathbf{x}}_e^i + \mathbf{K}_e^i\Delta\mathbf{x}_e^i) = \mathbf{f} \end{cases} \tag{7}$$

$\forall i = 1, \ldots, N$ contact points, where $\mathbf{f}_b$ is the contact force effect at the base, due to the impedance balance in (5). In the Laplace domain, the system in (7) becomes:

$$\begin{cases} (Ds + K)(X(s) - X^0(s)) = F \\ (M_b s^2 + D_b s + K_b)X_b(s) = F_b \end{cases} \tag{8}$$

where the interaction discrete-points model is replaced by (3) and the control law in (1) becomes

$$X^0(s) = K_p\left(\frac{E_f}{K_e} - X_b(s)\right) \tag{9}$$

replacing equation (9) in the controlled system dynamics (8), the force balance is expressed as:

$$(Ds + K)\left(X(s) - K_p\left(\frac{E_f}{K_e} - X_b(s)\right)\right) = F \tag{10}$$

Considering the base model in (8), the base displacement is

$$X_b(s) = \frac{F^0 - E_f}{M_b s^2 + D_b s + K_b} \tag{11}$$

that returns the closed-loop system

$$\begin{aligned} &(Ds + K)X(s) = \\ &\quad K_p\left(\frac{Ds + K}{M_b s^2 + D_b s + K_b} + \frac{Ds + K - K_e}{K_e}\right)E_f \\ &\quad + \left(1 + K_p\frac{Ds + K}{M_b s^2 + D_b s + K_b}\right)F^0 \end{aligned} \tag{12}$$

Considering F^0 a stable closed-loop reference, any instability in the system (12) could only arise from E_f. The force-tracking error transfer function $G_{ft}(s)$ is then expressed as:

$$G_{ft}(s) = \frac{E_f}{X(s)} = \frac{K_e}{K_p}\frac{b_0 + b_1 s + b_2 s^2 + b_3 s^3}{a_0 + a_1 s + a_2 s^2 + a_3 s^3} \tag{13}$$

where:

$$\begin{aligned} b_0 &= K + K_b & a_0 &= K_e K + K K_b - K_e K_b \\ b_1 &= K D_b + K_b D & a_1 &= K_e D + K D_b + K_b D - K_e D_b \\ b_2 &= K M_b + D D_b & a_2 &= M_b K + D_b D - M_b K_e \\ b_3 &= M_b D & a_3 &= M_b D \end{aligned}$$

The close-loop system behavior depends predominantly on the combination of environmental and base stiffnesses and the control gain K_p. The formulation in (12)-(13) is therefore used for analyzing the response of a single degree-of-freedom simulated system (in Section III) in relationship with major influencing parameters. Results form the analysis phase are then used for designing the actual control law and tuning the observers in (1) in a real system performing a controlled-force insertion task (in Section IV).

III. ANALYSIS OF COUPLED-SYSTEM DYNAMICS

In order to evaluate the influence of the to-be-compensated compliance of the base, some single-DoF simulations of the model in (7) have been executed, varying the values of base, controlled robot and interacting environment stiffnesses (K_b, K and K_e, respectively).

A. Influence of base compliance on tracked force

In force-tracking applications, the base deformation results in a degradation of time response performances due to the disturbances introduced by an additional non-modelled compliance. A feedforward step reference X^0 in robot pose (computed as in (1) according to desired F^0) produces, in fact, a regime loss of applied force ΔF_∞ absorbed by the base deformation. The magnitude of such effective force loss w.r.t. the rigid base case in depicted in Fig. 3. The greater the ratio between the environment stiffness and the base stiffness[1], the larger the ΔF_∞ to recover by the feedback action on sampled force ($\mathbf{f}$ in Fig. 2).

Estimating the effective interaction point w.r.t. which the

[1]Recall that stiff environments, relatively-soft mountings and compliant behaviors in impedance control are somehow the elective configuration in many manipulation tasks.

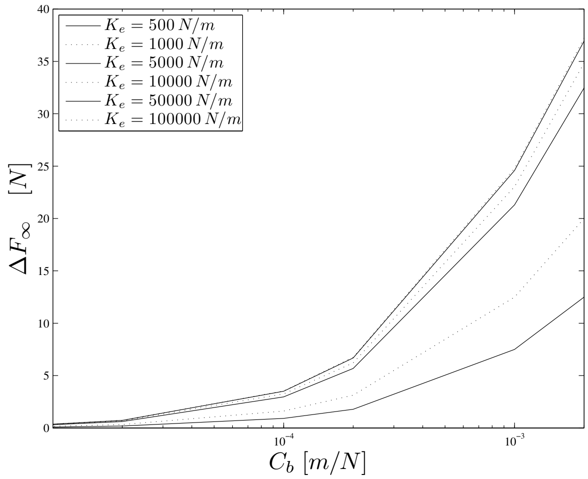


Fig. 3: Magnitude of force lost in relationship with base compliance $C_b = K_b^{-1}$ for some magnitudes of environment stiffnesses K_e.

control law (1) provides the reference pose, results in a faster response. The feedback response to a F^0 step reference is depicted in Fig. 4 with and without the base compensation. Without compensation, the pose reference updated by K_p gain on the basis of the force tracking error is systematically underestimated because of the displacement of the base. The model of base deformations, instead, enables the controller to observe the actual configuration under dynamics balance. The response peformances, nonetheless, depend on the readiness and accuracy of the base deformation observer.

B. Influence of stiffnesses on closed-loop control gain

The closed-loop control gain $K_p^\star$ has the equivalent effect of increasing the stiffness of the environment in order to augment the capability of the robot control in rejecting the force error e_f. Analyzing the transfer function G_{ft} in (13), is possible to define a map of the critical gains $K_p^\star$ as a function of the system stiffnesses configuration (see Fig. 5). Morphologically, the gain landscape is homogenous (from 500 to 1000 N/m) because of the softness of robot impedance

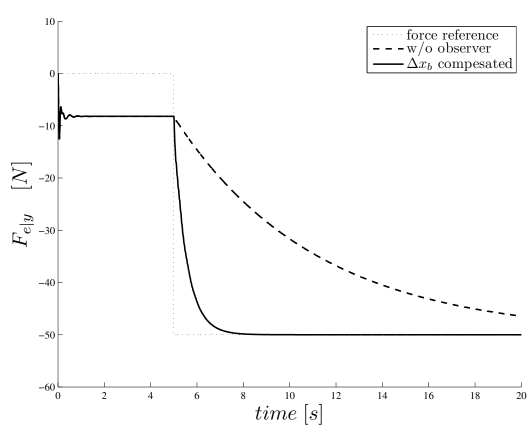


Fig. 4: Close-loop response to a F^0 step.

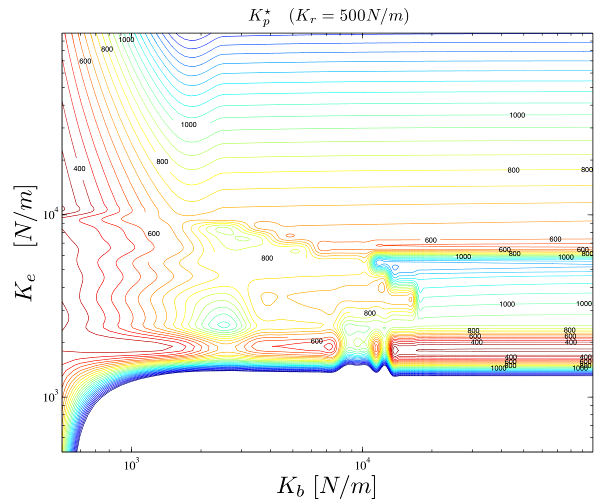


Fig. 5: Map of values of critical gain $K_p^\star$ given a combination of the stiffness of the robot base K_b and the stiffness of the interacting environment K_e. Single view for robot stiffness $K = 500\ N/m$. The closed loop stability is achieved for any combination of robot base and interacting environment. The plot shows that higher values for the proportional gain can be used as the interacting environment becomes softer and the robot base becomes stiffer.

behavior (aiming at limiting excessive force overshoots at the contact detection) and all dampings are imposed at critical values. Therefore, the control stiffness could be safely increased tuning the gain uniformly in the region with K_e both larger than K_b and $10e4\ N/m$ (relatively soft). Conversely, in the complemenary region, the system may trigger natural frequencies placed according to the stiffnesses configuration.

IV. Experimental example

The experimental set-up (see Fig. 6) includes a lightweight manipulator mounted on a cart allowing a single horizontal movement. The stiffnesses of the experimental systems are possibly selected in order to have some of the worst case conditions discussed in Section III: K_b is equal to $5000\ N/m$, the environment has low stiffness in vertical direction ($\approx\ 1000\ N/m$) and medium-hard stiffness on planar directions ($\approx 50000\ N/m$). A LASER position sensor is used for the evaluation of the base position estimation.

A. Base offline estimation

The online estimation of the base position relies on previous knowledge of the dynamic parameters of the mounting. The base model is obtained using a regular identification procedure on motion data (*i.e.* accelerations) sampled[2] at the base during an auto-excitation provided by the robot in a given configuration. The pattern is a logarithmic $[0-10]\ Hz$ chirp of the end-effector pose along all 3 traslational and 3 rotational axes, with amplitude of $5\ mm$. The total chirp duration is $200\ s$ and the reference pose of the robot is update

[2]Accelerometers are only needed for the dynamic parameters identification procedure.

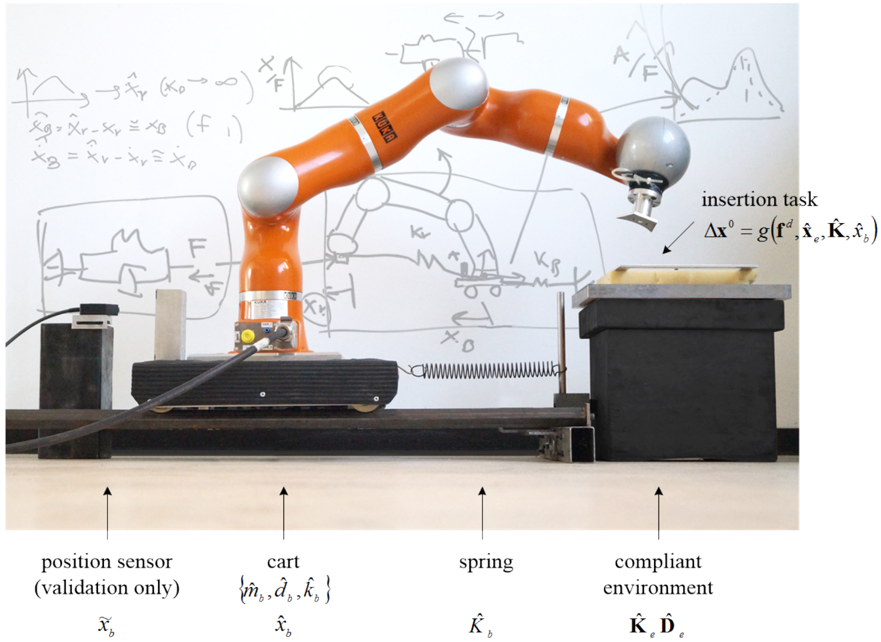


Fig. 6: Experimental setup for full rigid-body insertion task on soft environment. Robot mounted on 1 DoF compliant base.

every 5 ms. Robot pose measurement (for force projection) is updated at 200 Hz, acelerations at 2000 Hz. The base model is evaluated through a modal analysis, defining the Frequency Response Funtions (FRFs) of the base system between comanded robot poses and measured accelerations.

B. Force-tracked insertion task.

The assembly task (see [16] for discussion) is done in 4 major phases:

Phase A. Approach and contact detection.

Phase B. Exploration along translation components and on-line estimation of $\hat{\mathbf{K}}_e$. The impedance control set-point $\Delta\mathbf{x}^0$ is computed as a function of force-tracking error $\mathbf{e}_f = \mathbf{f}^d_{task} - \mathbf{f}$, with $\mathbf{f}^d = [15N\, 15N\, 10N\, 0\, 0\, 0]^T$ (rotational components of $\Delta\mathbf{x}^0$ are blocked).

Phase C. Assembly proper, enabling rotations for insertion and relying on $\widehat{\mathbf{K}}_e$ observed along the searching directions. The set-point $\mathbf{f}^d$ enables also torques.

Phase D. After tight assembly, on-line estimation of (possibly changing) $\widehat{\mathbf{K}}_e$.

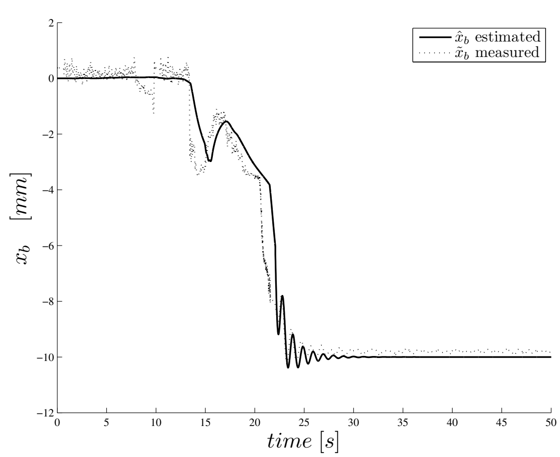
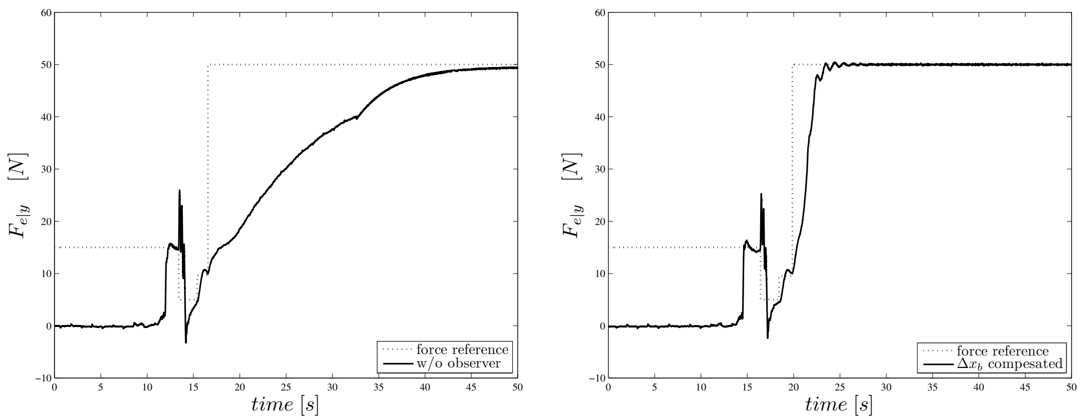


Fig. 7: Cart position during task execution.

During phases B and D, the base displacement x_b is estimated and measured with the external sensor (see Fig. 7). Possible sources of x_b estimation errors could include filter time constants tuning, inaccurate force sampling and inaccuracies in the linear mass-spring-damper model of the base.

In Fig. 8 the effect of the base compensation along the described task is displayed for a single selected direction (Y). During phase A, the robot is moving only in Z direction and no force is measured in Y direction. During phase B, reference force f^d_y is set equal to $15N$ in order to achieve smooth first contact in Y. During phase C, f^d_y has a lower value in order to allow the rotation of the insertion geometry without fails in the task execution. During phase D, the reference force f^d_y is set to $50N$ in order to have a tight assembly of the parts (process requirement). Reference force f^d_y is superimposed as a step reference between the different phases. In Fig. 8-(a) the task-D execution without base compensation is entirely in charge of the force error gain, while in Fig. 8-(b) the base estimation and compensation allows a much faster f^d_y response. It should be noted that for all cases, regardless the base compensation, the measured force in the contact phase (phase B) presents some spikes. This could be due to the fact that the multi-point geometric contact model is not taken into account and that the controller is purely proportional. Additionally, some residual estimation delays likely due to estimation-filter tuning combined with force sampling rate, could affect the fastest phenomena in the assembly.



(a) (b)

Fig. 8: Force tracking along different phases of an assembly task without (a) and with (b) compensation of base deformation.

V. CONCLUSIONS

Based on force-tracking control laws, the introduced interactin control strategy with compliant mounting has been implemented and tested in a full rigid body assembly real task. An impedance balance set-point has been generated using the estimation of the base deformation due to the task execution. The execution strategy uses distribution of forces and the on-line estimate of the stiffness of the interacting environment through an EKF. The developed control has been compared with absence of compensation for the unknown base position. Results show some promising effects in control response. The introduced control strategy can be fairly generalized in full rototranslation of the executed task. As the impedance control decouples the robot 6 DoFs, all task-space coordinates can be independently controlled using the defined control algorithm. The base compliance observer can be expanded to full DoFs as well, being the computation power linear and deterministic with the size of EKF. Further experimental studies will consider a 3D (2 translations, 1 rotation) compliant base. In order to improve the control performaces, a non-linear model of the robot base is considered for upgrading the estimate, together with the derivative terms in the control loop and nonlinearities in the contact and environment stiffness observers.

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