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An interaction controller formulation to systematically avoid force overshoots through impedance shaping method with compliant robot base

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A B S T R A C T

Nowadays, light-weight manipulators are widely adopted in many applications requiring manipulation/interaction with compliant/fragile objects. Reduced inertia and controlled compliance, indeed, make such manipulators particularly attractive when compliant mountings (or mobile platforms) are adopted and contact force overshoot may compromise the application. The here presented work proposes the design of a force-tracking controller for interaction tasks allowing to systematically avoid any force overshoot for lightweight robots mounted on compliant bases. The developed algorithm allows to compensate for the compliant robot base dynamics that affects the interaction. The control gains are calculated to track a target force reference through the estimation of the robot base state and the interacting environment stiffness. Closed-loop stability and control gains calculation are described. The control law has been validated in a probing task involving a compliant robot base and a compliant environment to show the obtained performance.

1. Introduction

Robotics applications are increasingly devoted to dynamically changing environments, where the task involves both the interaction at the robot end-effector with the environment (*i.e.*, assembly, technological tasks, *etc.*) and the re-location of the manipulator (*i.e.*, robot on mobile platform). Light-weight manipulators are often mounted on mobile platforms (Fig. 1), having reduced inertia (allowing to easily re-locate the manipulator) and controlled compliance (allowing to safely interact with the environment). However, the mobile platform limited stiffness introduces compliance affecting the task dynamics. Indeed, such applications display two interacting ports [1]: the contact point(s) between the manipulator tool and the environment, and the ground connection(s) of the robot base. The corresponding coupled dynamics results in decreasing the robot controlled bandwidth and, possibly, in task failures. In fact, the coupled interaction may result in force overshoots, damaging components and compromising the task execution, and many applications such as [2–5] show critical force control needs to avoid the failure of the task.

1.1. Literature overview

Despite numerous researches has presented many interaction tasks using light-weight robots, almost all of them face only a single goal (*i.e.*, control the interaction robot tool - target environment, or compensate for the robot base dynamics to reduce robot tool oscillations). Indeed, few researches present control laws taking into account whole system: the contact model, the elastic model of the robot ground connection and the force contact overshoot limitations.

1.1.1. Robot tool - target environment interaction

Two families of controllers have been proposed to track a target interaction: impedance (and admittance) controllers [6–8], and pure force controllers [9]. Even if such controllers are demonstrated to be equivalent [10], the application areas are different: pure force control schemes are preferred when compliance in the force/torque sensor or in the robot joints [11,12] is present, while impedance controllers are preferred to interact with partially unknown environments, allowing the definition of the target dynamics for the controlled robot. Further, to achieve a fine tracking different methods have been developed based on the impedance control. While some methods are based on the energy tank theory to preserve the passivity of the controlled system [13,14], many works are directly adapting the impedance control parameters based on

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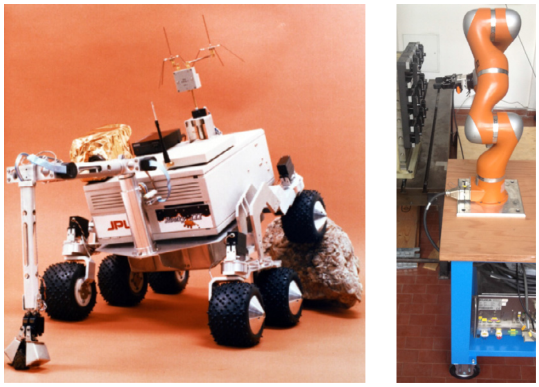

a) b)

Fig. 1. A couple of target scenarios are shown. In a), a light-weight manipulator is mounted on a mobile platform for planetary exploration (NASA-JPL, from http://www.tumblr.com). In b), an assembly tasks is shown. The manipulator is mounted on a passive mobile base to allow re-location. Mobile platform wheels introduce compliance in the robot base, deforming during the interaction (ITIA-CNR labs).

the interaction force and can be divided in two main families: (a) set-point deformation [15–18] and (b) variable impedance adaptation [19–21].

For class (a), the impedance control set-point is modified on the base of the estimated environment stiffness and of the force-tracking error. Commonly, such approaches maintain a constant dynamic behavior of the robot, so that when the environment stiffness quickly changes, the bandwidth of the controllers results limited. Class (b) methods introduce the modification of the impedance parameters during the task execution. Common solutions consist on gain-scheduling strategies that select the stiffness and damping parameters from a predefined set on the basis of the current state. Such approaches are used in tasks with a stationary, known and structured environment. Both classes (a) and (b) do not deal with the avoidance of force overshoots.

1.1.2. Compensation of the robot base dynamics

There is a plethora of papers dealing with compliant/mobile robot bases applications, defining classifications, design methods, modeling and control algorithm for vehicle-manipulator systems [22–30].

Considering the target application scenario (*i.e.*, light-weight manipulators mounted on flexible/mobile platforms to execute high-precise interaction applications), the robot base motion compensation is of primary importance to avoid any instability or force overshoot that may compromise the task execution. Many works deal with such topic. [31–34] are taking into account compliant robot bases but such works do not deal with force-tracking performance. In particular, [31] investigates the case of gravitation-free application, while [32] highlights the influence of single terms on the coupled-system dynamics in the case of standard gravitation load. [33] considers flexible structure mounted manipulator and it focuses on algorithms to avoid base vibration, while [34] considers a direct measurement of the base oscillation as a feedback to modulate the manipulator actuator input. Finally, the few works [35–37] that model the base-robot-environment interaction considers only sub-problems of the whole task. Indeed, [35] focuses on how to guarantee smooth transition from a free-space motion to contact with an unknown environment, while [36,37] considers known (bound) base stiffness, in order to tune the actual manipulator stiffness to the desired one. In addition, to the best of the authors' knowledge, no work suggests force controllers directly taking into account compliant robot bases and no work considers controllers that avoid force overshoots while taking into account the robot base elasticity.

1.2. Work contribution

Authors have already investigated such control applications. As a first study, the rigid robot base scenario has been considered, developing class (a) controllers [38–40] and class (b) controllers [41]. Then, the compliant robot base scenario has been studied. In [42] a class (a) controller has been proposed to compensate for the compliant robot base dynamics without considering the force overshoots avoidance. In [43], a class (b) controller has been proposed, extending the previous work, to guarantee the force overshoots avoidance. In that work, the impedance control parameters (*i.e.*, stiffness and damping) were adapted based on the force tracking error. Although the experimental validation shows the capabilities of the defined controller to avoid force overshoots, authors were not able to analytically calculate the control gains, having a time-variant closed-loop system (stiffness and damping functions of time).

In this paper, extending the previous works, a class (a) control law to systematically avoid any force overshoot in interaction tasks is proposed for a light-weight manipulator (a KUKA LWR 4+ is used) involving compliant environments with (partially) unknown geometrical and mechanical properties and a compliant robot base. Based on the force-tracking impedance control, the algorithm modifies the impedance control set-point to obtain a linear closed-loop system and analytically calculate the control gains (i) to compensate for the base robot dynamics, while (ii) systematically avoiding force overshoots during the force tracking task. The impedance control set-point is calculated to shape the impedance of the controlled robot based on the estimate of the force error, the robot base deformation and the environment stiffness. An Extended Kalman Filter (EKF) is implemented to estimate the environments parameters, while a Kalman Filter (KF) is implemented to estimate the robot base position to be used as feedback to avoid the use of external sensors. Although the proposed algorithm show a "simple" structure (PD control structure based on the estimation of the environment stiffness - EKF - and robot base motion - KF), it combines the capabilities of force tracking state-of-the-art methods without robot base dynamics compensation with the capabilities of state-of-the-art robot base dynamics compensation methods. Combining such approaches, the proposed method is capable to track a target force also compensating for the compliant robot base dynamics (*i.e.*, having zero steady state force tracking error without force overshoots). The control strategy stability and the closed-loop bandwidth are analyzed and the analytically calculation of the control gains is described. A probing task has been performed in order to show the force overshoots avoidance. A second KUKA LWR 4+ has been used as target interacting environment to set a target (not shared) environment stiffness.

2. Coupled interaction dynamics

2.1. Closed-loop light-weight robot dynamics

The KUKA LWR 4+ enables a task space visco-elastic behavior [44], with decoupled tunable equivalent Cartesian stiffness $\mathbf{K}_r := diag(k_{r,1}, \dots, k_{r,6})$ and decoupled damping $\mathbf{D}_r := diag(d_{r,1}, \dots, d_{r,6})$. On the basis of experimental outcomes [45], also the robot mass can be described by a decoupled inertia $\mathbf{M}_r := diag(m_{r,1}, \dots, m_{r,6})$. Thus, taking into account the acceleration of the robot base $\ddot{\mathbf{x}}_b$, a good approximation of the real behavior of the robot up to 5 Hz is (Fig. 2):

$$\mathbf{M}_r(\ddot{\mathbf{x}}_r + \ddot{\mathbf{x}}_b) + \mathbf{D}_r\dot{\mathbf{x}}_r + \mathbf{K}_r\Delta\mathbf{x}_r = \mathbf{f}_r, \quad \text{with,} \quad \Delta\mathbf{x}_r := \mathbf{x}_r - \mathbf{x}_r^0 \qquad (1)$$