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High-accuracy robotized industrial assembly task control schema with force overshoots avoidance☆

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ABSTRACT

The presented paper proposes an analytical force overshoots free control architecture for standard industrial manipulators involved in high-accuracy industrial assembly tasks (*i.e.*, with tight mounting tolerances). As in many industrial scenarios, the robot manipulates components through (compliant) external grippers and interacts with partially unknown compliant environments. In such a context, a force overshoot may result in task failures (*e.g.*, gripper losses the component, component damages), representing a critical control issue. To face such problem, the proposed control architecture makes use of the force measurements as a feedback (obtained using a force/torque sensor at the robot end-effector) and of the estimation of the *equivalent interacting elastic system* stiffness (*i.e.*, *force sensor– compliant gripper–compliant environment* equivalent stiffness) defining two control levels: (i) an internal impedance controller with inner position and orientation loop and (ii) an external impedance shaping force tracking controller. A theoretical analysis of the method has been performed. Then, the method has been experimentally validated in an industrial-like assembly task with tight mounting tolerances (*i.e.*, H7/h6 mounting). A standard industrial robot (a Universal Robot UR 10 manipulator) has been used as a test-platform, equipped with an external force/torque sensor Robotiq FT 300 at the robot end-effector and with a Robotiq Adaptive Gripper C-Model to manipulate target components. ROS framework has been adopted to implement the proposed control architecture. Experimental results show the avoidance of force overshoots and the achieved target dynamic performance.

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1. Introduction

1.1. Robotized assembly task

Robotic assembly tasks have been widely investigated since the early 80s (Fox & Kempf, 1985; Sanderson & Perry, 1983). Nevertheless, such task is still a challenging application as tight mounting tolerances (Chen et al., 2007), uncertainties on mechanical/geometrical properties of the manipulated/interacting parts (Saric, Xiao, & Shi, 2014) and critical components (Popa & Stephanou, 2004) are increasingly involved. In fact, many applications require high-precision assembly of critical parts, such as space applications (Doggett, 2002; Rembala & Ower, 2009), aircraft industries (Jayaweera & Webb, 2007; Jayaweera, Webb, & Johnson, 2010; Zhang, Hu, Yi, Fu, & Tang, 2014) and electronic components industries (Stolt, Linderoth, Robertsson, & Johansson, 2013). Moreover, to improve the flexibility of the assembly, multi-robot co-operation and human–robot co-operation are often required (Stroupe et al., 2006; Zhang & Knoll, 2003).

The optimization of industrial assembly applications relies on many interdisciplinary topics, such as task planning (De Mello & Scaramelli, 0000; Rampersad, 1994), robot planning (Carlson, Spensieri, Söderberg, Bohlin, & Lindkvist, 2013; Chen, Di, Huang, Sasaki, & Fukuda, 2009) and computer vision (Choi, Taguchi, Tuzel, Liu, & Ramalingam, 2012; Davies, Peña Cabrera, Lopez-Juarez, Rios-Cabrera, & Corona-Castuera, 2005; Kruger & Thompson, 1981; Nelson, Papanikolopoulos, & Khosla, 1993). The manipulator control design is one of the most investigated topics. Since first studies (Newman et al., 1999), force/dynamics control is the most adopted control strategy to perform assembly tasks, also involving visual servoing. In Abdullah, Roth, Weyrich, and Wahrburg (2015) visual servoing and force/torque measurements are combined in order to define a strategy to perform assembly tasks with geometrical uncertainties. In Cheng and Chen (2014) and Marvel et al. (2009) the optimal parameters for the assembly task execution are learned in subsequent trials. In Kim, Kim, Song, and Son (2011) the impedance control is used in order to deal with

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positioning errors/inaccuracies. In Stolt, Linderoth, Robertsson, and Johansson (2012) a force control algorithm has been developed without the use of an external force sensor, while (Sahu, 0000) proposes the use of such external sensor to perform the assembly task. Moreover, many efforts have been made in the contact estimation and state transitions identification during the task execution (Liao & Leu, 1998; McCarragher & Asada, 1993) to improve the force control algorithms.

However, in the best knowledge of authors, no contributions are devoted to avoid force overshoots while performing an assembly task. Such requirement is of primary importance when the manipulator is assembling fragile components and manipulating parts through compliant grippers (Stolt et al., 2013). In fact, in such scenarios, even small force overshoots may damage the manipulated component or cause the loss of the component from the gripper, compromising the application.

1.2. Interaction control

In order to identify an interaction controller analytically avoiding force overshoots, authors have taken into account the interaction control literature. In particular, since the milestones (Mason, 1981; Raibert & Craig, 1981; Salisbury, 1980), impedance control (Hogan, 1984) has been particularly effective in order to interact with compliant environments, including also non-restrictive assumptions (Colgate & Hogan, 1989) on the dynamical properties of the target compliant environment. In fact, with respect to pure force controllers (Lange, Bertleff, & Suppa, 2013; Lange, Jehle, Suppa, & Hirzinger, 2012), impedance control compounds an easier tunable dynamic balance response for the robot. In addition, particular design of impedance controllers (Ott, Mukherjee, & Nakamura, 2010), grants a wide control bandwidth, thanks to a continuous adaptation of the controller.

Nevertheless, some force/deformation regulation requirements are introduced in order to improve the robustness and safety of interaction with a dynamic task, especially in the case of a precision-force process (Roveda, Vicentini, & Molinari Tosatti, 2013). Although impedance methods are proved to be dynamically equivalent to explicit force controllers (Volpe & Khosla, 1995), a direct tracking of explicit interaction forces is not straightforwardly allowed.

To overcome this limitation and preserving the properties of the impedance behavior two different families of methods have been mainly introduced: class (a) force–position tracking impedance controllers and class (b) variable impedance controllers.

Common solutions of class (a) methods is suggested in Villani, Canudas de Wit, and Brogliato (1999), where the controlled force is derived from a position control law, scaling the trajectory as a function of the estimated environment stiffness, calculating the time-varying PID gains. Another important approach (Jung, Hsia, & Bonitz, 2004; Seraji & Colbaugh, 1993, 1997) involves the generation of a reference motion as a function of the force-tracking error, under the condition that the environment stiffness is variously unknown, *i.e.* estimated as a function of the measured force.

Common solutions of class (b) methods relies on gain-scheduling strategies that select the stiffness and damping parameters from a predefined set (off-line calculated) on the basis of the current target state (Ferraguti, Secchi, & Fantuzzi, 2013; Ikeura & Inooka, 1995). Lee and Buss (2000) varies the controlled robot stiffness on-line to regulate the desired contact force based on the previous force tracking error, without any knowledge of the environment. Yang et al. (2011) presents a human-like learning controller to interact with unknown environments that feedforward adapts force and impedance. Oh, Woo, and Kong (0000, 2014) describes a frequency-shaped impedance control method shapes a disturbance observer in the frequency domain so that the impedance is manipulated to achieve both the compliant interaction and reference tracking.

Commonly in class (a) methods, all approaches maintain a constant dynamic behavior of the controlled robot, so that when the environment stiffness quickly and significantly changes, the bandwidth of the controllers has to be limited for avoiding instability, while in class (b) methods, stationary, known and structured environments are considered. Moreover, no contributions are related to specifically avoid force overshoots during a task execution.

1.3. Paper contribution

Authors have already investigated interaction controllers, developing class (a) controllers (Roveda et al., 2016; Roveda et al., 2013; Roveda, Vicentini, Pedrocchi, & Molinari Tosatti, 2015) and class (b) controllers (Roveda, Vicentini, Pedrocchi, Braghin, & Molinari Tosatti, 2014). In particular, in Roveda et al. (2015) authors were able to define a free force overshoots algorithm, testing it on a KUKA LWR 4+ manipulator in a simple scenario (a simple probing task has been performed).

The aim of this work is to apply the algorithm proposed in Roveda et al. (2015) to a standard industrial robot to execute a real industrial assembly task with tight mounting tolerances. In fact, the KUKA LWR 4+ manipulator provide non-standard and high-performance features: high-rate control frequency (200 – 500 Hz), native high-performance impedance control availability, torque sensors at each joint to directly measure external forces and implement low-level torque control. Such features are not commonly available on standard industrial robots, requiring to deal with low-rate control frequency (< 100 Hz), to implement compliant controllers usually based on the native position control of the manipulator and using external filtered force measurements (obtained from force/torque sensor mounted at the robot end-effector) to implement interaction control. Therefore, with respect to the previous work, the target scenarios includes a compliant gripper and a force sensor at the robot end-effector, defining the *equivalent interacting elastic system* as the series of *force sensor – compliant gripper – compliant environment*.

The proposed control architecture makes use of the force measurements as a feedback and of the estimation of the equivalent interacting elastic system stiffness. Two control levels are defined: (i) an internal impedance controller with inner position and orientation loop and (ii) an external impedance shaping force tracking controller. A theoretical analysis of the closed-loop bandwidth of the coupled system *controlled robot – equivalent interacting elastic system* has been performed, taking into account the interaction dynamics and the control gains. The method has been validated in an industrial-like assembly task with tight mounting tolerances (*i.e.*, H7/h6 mounting). Such high-precision assembly tasks require a refined force control to avoid that sticking/not sliding behaviors of the component may compromise the task. In fact, without a high-performance controller, such effects may result in an incomplete insertion of the component. A standard industrial robot (a Universal Robot UR 10 manipulator) has been used as a test-platform, equipped with an external force/torque sensor Robotiq FT 300 at the robot end-effector and with a Robotiq Adaptive Gripper C-Model to manipulate target components. The control algorithms have been implemented adopting the Robotic Operating System (ROS) framework (ROS, 2015; Cousins, Gerkey, & Conley, 2010). Experimental results show the avoidance of force overshoots and the achieved target dynamic performance while executing the assembly task.

2. Equivalent interacting elastic system

2.1. Dynamics modeling

The *equivalent interacting elastic system* identifies the equivalent system composed by the series of *force sensor – compliant gripper – compliant environment*. In fact, such elastic serial system can be considered as an equivalent dynamic system for the purpose of the control design.

Denoting $\mathbf{D}_e$ and $\mathbf{K}_e$ as the equivalent interacting elastic system damping and stiffness respectively, the equivalent interacting elastic system dynamics can be modeled as follows (Flügge, 1975) (Fig. 2):

$$\mathbf{f}_e = -\left(\mathbf{D}_e \dot{\mathbf{x}}_e + \mathbf{K}_e \, \Delta \mathbf{x}_e\right). \tag{1}$$

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