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Guaranteeing stable tracking of hybrid position–force trajectories for a robot manipulator interacting with a stiff environment☆

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ABSTRACT

This work considers the control of a manipulator with the aim of executing desired time-varying motion–force trajectories in the presence of a stiff environment. In several situations, the interaction with the environment constrains just one degree of freedom of the manipulator end-effector. Focusing on this contact degree of freedom, a switching position–force controller is considered to perform the hybrid motion–force tracking task. To guarantee input-to-state stability of the switching closed-loop system, a novel stability result and sufficient conditions are presented. The switching occurs when the manipulator makes or breaks contact with the environment. The analysis shows that to guarantee closed-loop stability while tracking arbitrary time-varying motion–force profiles with a rigid manipulator, the controller should implement a considerable (and often unrealistic) amount of damping, resulting in inferior tracking performance. Therefore, we use the stability analysis technique developed in this paper to analyze a manipulator equipped with a compliant wrist. Guidelines are provided for the design of the wrist compliancy while employing the switching control strategy, such that stable tracking of a motion–force reference trajectory can be achieved and bouncing of the manipulator against the stiff environment can be avoided. Numerical simulations are presented to illustrate the effectiveness of the approach.

1. Introduction

Numerous applications such as, e.g., bilateral teleoperation, automated assembly tasks, and surface finishing involve the interaction between a robot manipulator and a stiff environment. In those applications, a *time-varying motion profile* should be tracked during free motion, whereas during constrained motion a *time-varying force profile* should be applied on the environment. The stability of the fast transitions from free motion to constrained motion and from constrained motion to free motion is essential for the tracking of such time-parameterized *time-varying motion–force profiles*. Ensuring stability during these transitions is a challenge as the combined robot–environment dynamics switches abruptly at the moments of establishing contact with and detachment from the environment. The aim of this paper is to propose a novel approach to analyze stability of this switched system, while tracking time-varying motion–force profiles. The need for this stability analysis originates particularly from our interest in telerobotics, where a force and position reference from the master device has to be translated into a command for the slave device. As the force and position reference comes from a human operator, we aim to treat generic reference signals.

Over the past decades, different control architectures have been proposed for motion–force control of a manipulator in contact with a stiff environment (for an overview, see, e.g., Siciliano & Khatib, 2008, Chapter 7). The most studied and applied control schemes include stiffness, impedance and admittance control (Canudas de Wit & Brogliato, 1997; Ge, Li, & Wang, 2014; Hogan, 1988; Jung, Hsia, & Bonitz, 2004; Volpe & Khosla, 1993; Zotovic Stanisic & Valera Fernández, 2012), hybrid position–force control (Khatib, 1987; Raibert & Craig, 1981), and parallel position–force control (Chiaverini & Sciavicco, 1993). While these approaches usually exhibit sufficient robustness to be used in practice, a formal mathematical proof of stability is still lacking. Typically, the gains in these control schemes are tuned separately for free motion and constrained motion. Stability of the resulting closed-loop dynamics is analyzed using standard Lyapunov methods and guaranteed for free motion and constrained motion independently, but the contact and detachment transitions are not included in the analysis. Bouncing

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and unstable contact behavior might therefore still occur, and do still occur. As a practical solution, when implementing these control schemes on a physical manipulator, the manipulator is usually commanded to approach the environment with a very slow velocity to prevent the excitation of the unstable contact dynamics.

From an analysis perspective, only a few theoretical studies have addressed directly the instability resulting from bouncing of the manipulator against a stiff environment. In Tarn, Wu, Xi, and Isidori (1996) and Doulgeri and Iliadis (2005), a switched position–force controller is considered, where the controller switches from motion to force control when contact with the environment is made. Using analysis techniques for switched systems, conditions for asymptotic stability are derived for a *constant* position or force setpoint regulation problem. Hysteresis switching is considered in Carloni, Sanfelice, Teel, and Melchiorri (2007) to prevent bouncing of the manipulator against the environment. In Pagilla and Yu (2001), the number of bounces is cleverly minimized by exploiting a transition controller, but then the contact force is controlled to a *constant* setpoint. In Lai et al. (2012), nonlinear damping is proposed to minimize the force overshoot without compromising the settling time. In all these publications, tracking of desired *time-varying* motion and force profiles is not considered.

A popular approach to prevent unstable impacts is impedance control (Albu-Schaffer, Ott, & Hirzinger, 2007; Canudas de Wit & Brogliato, 1997; Jung et al., 2004). In the outer loop, the contact force is controlled by creating a desired impedance specified for the contact dynamics to compute a requested motion profile for the inner motion control loop. Consequently, the contact force is controlled indirectly, such that tuning the impedance parameters requires a trade-off between motion control, force control and stabilizing the effect of impacts. To alleviate the compromising effect of this trade-off on the tracking performance, the proportional gain is adapted online in Jung et al. (2004), whereas in Canudas de Wit and Brogliato (1997) the desired impedance is temporarily scaled during the transition phase. In Zotovic Stanisic and Valera Fernández (2012), the impedance parameters are switched online to dissipate the kinetic energy engaged at impact. The proposed controller guarantees velocity regulation in free motion and tracking of a *constant* force setpoint in contact. For other forms of compliant control, such as variable impedance actuation, the interested reader is referred to Vanderborght et al. (2013). To the best of our knowledge, a formal stability proof that includes in the analysis the free motion to contact transitions, while tracking arbitrary time-varying motion–force profiles, does not yet exist in the context of impedance and compliant control.

In the above mentioned papers, the manipulator–environment interaction is modeled using a flexible spring–damper contact model. The stiffness and damping properties of the environment are included explicitly and, as a consequence, the impact phase has a finite time duration. Such a modeling approach is also taken in this paper.

Manipulator–environment interaction can also be modeled using tools from nonsmooth mechanics (Brogliato, 1999; Leine & van de Wouw, 2008). In doing so, the time duration of the impact event is assumed to be zero and an impact law (e.g., Newton's law of restitution) is employed to characterize the collision. Stable tracking of specific force/position profiles using such nonsmooth mechanics modeling formalism has been addressed in this context. In Pagilla (2001), a discontinuous control scheme is proposed to ensure stable regulation on the surface of the unilateral constraint. A switched motion–force tracking controller for manipulators subject to unilateral constraints is considered in Brogliato, Niculescu, and Orhant (1997), Bourgeot and Brogliato (2005) and Morărescu and Brogliato (2010). There, it is shown that the design of the desired trajectory in the transition phase is crucial for achieving stability. To the best of authors' knowledge, the problem of stable tracking of arbitrary force/position profiles as we consider in this work has not been solved even in the framework of nonsmooth mechanics. The stability of the tracking controller cast in this framework is clearly of interest and deserves further investigation. This framework will not be addressed here just because, as we mentioned, we adopt a flexible (spring–damper) contact model.

In this work, we propose a mathematical analysis that can help control engineers as well as mechanical designers to develop controlled manipulators that exhibit stable contact behavior with a stiff environment, while tracking a time-varying motion and force profile. Because in many tasks of practical interest the interaction of the robot end-effector with the environment occurs just in one direction, we study the contact stability problem using a 1-DOF dynamic manipulator model. The remaining unconstrained DOFs can be controlled with standard motion control techniques (see Spong, Hutchinson, & Vidyasagar, 2006). For illustration purposes, we consider a switched motion–force tracking control strategy and we analyze stability of the resulting closed-loop dynamics. The obtained stability conditions are given in Theorem 1 in Section 3. The stability analysis of the closed-loop system reveals that, due to the relatively stiff contact dynamics, the considered switched motion–force controller should implement a considerable amount of damping to guarantee stability while tracking an arbitrary time-varying motion–force profile. Because an excessive amount of damping limits the tracking performance due to a sluggish response, the contact dynamics are made compliant by using an alternative mechanical manipulator design that includes a compliant wrist. In this way, the resonance frequency of the impact and contact transients can be reduced and the associated energy can be dissipated in a passive way. The purpose of such a compliant energy absorbing component is similar to that of an impedance or compliant controller.

The main contributions of this paper are as follows. First, we propose a combination of the compliant wrist design with a switched motion–force controller for the tracking of time-varying motion and force profiles. Secondly, we propose a stability analysis that provides design guidelines for both the compliant wrist and controller to guarantee stable contact while tracking arbitrary motion and force profiles. In particular, we show that for realistic system parameter values, the compliant model exhibits a clear distinction between fast and slow time-scale dynamics. Using model reduction, we obtain models of reduced order for the free motion and contact phase, respectively, representing only the slow dynamics. In combination with the stability analysis developed for the rigid manipulator, we obtain guidelines for the parametric design of the compliant wrist such that bouncing of the manipulator against the stiff environment can be prevented without the need of a considerable amount of damping from the controller.

This article is organized as follows. In Section 2, the manipulator and environment model, and the considered switched motion–force controller are introduced. The stability analysis of the switched closed-loop system is described in Section 3. Section 4 illustrates the obtained results by means of a simulation study. Section 5 discusses the benefits of additional (wrist-)compliance in the manipulator and illustrates how to tune the parameters of the controller and the compliant wrist. Finally, the conclusions are presented in Section 6.

2. System modeling and controller design

Our primary goal is to make a manipulator track a desired time-varying motion–force profile. As explained in the introduction, we focus on a 1-DOF modeling of the manipulator–environment interaction.