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# On the stability and accuracy of high stiffness rendering in non-backdrivable actuators through series elasticity

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ABSTRACT

This paper addresses the problem of accuracy and coupled stability of stiffness-controlled series elastic actuators, where the motor is modeled as a non-backdrivable velocity source, and the desired value of virtual stiffness is above the physical stiffness of the compliant element. We first demonstrate that, in the mentioned conditions, no linear outer-loop force control action can be applied on the velocity-sourced motor to passify the system. Relaxing the constraint of passivity, we exhaustively search the control design space defined by parametric force and stiffness controllers, expressed in a general lead-lag form, and define a lead-type stiffness compensator that results in acceptable conditions for both coupled stability and accuracy. We also address the effect of a non-ideality in the velocity control loop, such as limited-bandwidth velocity control, and derive relationships between the value of the inner velocity loop time constant and parameters of the stiffness compensator that provide the best performance in terms of both stability and accuracy of haptic display.

We show that the parameters of a simple outer-loop stiffness compensator can be optimized to result in a stable and accurate display of virtual environments with stiffness values in a large range, that also comprises values of virtual stiffness *higher* than the physical stiffness of the compliant element. A requirement for coupled stability is that the actuator is designed such that the minimum value of inertia connected to the compliant actuator load is higher than a control-defined threshold. Finally, we extensively analyze how the minimum value of interaction mass for coupled stability can be minimized through modulation of the stiffness compensator zeros and poles, considering realistic limitations in the velocity control bandwidth of non-backdrivable motors. Our analysis, validated through both numerical simulations and experiments, opens the possibility for alternative approaches to the design of compliant actuators, whereby rendering of high stiffness is possible if the load mass is always higher than a determined threshold.

## 1. Background

The possibility of safe physical interaction and successful cooperation with humans is among the most promising and exciting frontiers of robotics. Several new scenarios such as rehabilitation robotics [1–3], human augmentation robotics [4], surgical robotics [5,6] and haptics have rapidly transitioned from science-fiction, to research laboratories to flourishing industries. In all those scenarios, a common underlying feature is the need of regulating the physical interaction between a human and a robot.

In order to achieve this goal, interaction control approaches, as described in the impedance control framework [7], have extensively been implemented, and their effectiveness demonstrated in several applications requiring physical interaction with humans. In the case of simple impedance control [7,8], the controller is defined in impedance causality, and the mechanism is modeled as a pure source of effort variables. Successful implementation of this type of impedance controller has been demonstrated mostly in the case of robots with negligible intrinsic dynamical properties or whose motion is approximated by quasi-static movements [1,9,3].

The problem of accurately regulating interaction becomes more difficult in the case of manipulators with complex dynamics, with high inertia, and/or with highly non-transparent actuation systems [10]. When robots are intended for applications requiring substantial assistance to humans during load-intensive tasks, manipulators are indeed not pure effort sources, due to the lack of actuation systems that allow achievement of high force density without substantial increase of task-space dynamic loading. In this

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case, model-based dynamic compensation schemes for impedance control can be adopted [11], but often do not fully guarantee accurate interaction control. In general, effectiveness of model-based schemes is limited by neglect of higher order or nonlinear dynamical effects, and by issues related to sensorization and practical limitations in the capabilities of full state feedback, required for compensation of inertial loads.

Force feedback, an approach pursued since the late 1970s [12], can enable the accurate regulation of interaction also in non-transparent manipulators. In such architectures, an explicit measurement of the force of interaction between the manipulator and the environment is used to generate a command signal, that ultimately regulates interaction with the environment. Since then, several forms have been proposed for the force controller, such as proportional control, pure integral control, proportional-integral (PI) control [11], and controllers with inner motion-control loops ([13,14] for compliant joints, and [15] for rigid actuators).

### *1.1. Passivity for force-feedback systems*

Real-world implementations of interaction control through force-feedback do not succeed in achieving arbitrary impedance values. In practice, when a controller attempts to emulate dynamics that differ significantly from those of the hardware, the risk of instability increases [16]. The stability limits in force-feedback controlled systems have been approached through the concept of passivity, a concept adapted from classical theory of electrical networks [16]. It has been proved that when two stable systems with passive impedance port function are coupled together, the coupled system, that results from the connection of the two systems, is stable. Instead, if a robot is stable but non-passive, there will be at least a passive environment that, during interaction, will destabilize the controlled system [16,17]. Proving passivity of a controlled system ensures stability for a wide range of interaction environments that include human dynamics, that are generally modeled as a passive, non linear, first- or second- order system. Also, passivity can be proved for a simplified model, that includes only the controlled system, and do not require detailed knowledge of the environment. Despite the introduced simplicity, this approach allows derivation of strong conclusions on the stability properties of the robot, when coupled to an extremely large and useful set of environments.

Requiring passivity has also drawbacks. Colgate showed that if endpoint force feedback is used to compensate for also the distal mass, the system becomes non-passive [17]. This limitation results from the often unavoidable presence of dynamics between the force sensor and the actuator, that can severely limit the performance of force and impedance controllers. Achievement of global passivity properties for a controller (i.e. passivity for all frequencies) is considered an important requirement for human-interacting robots; yet, at the same time, it is also acknowledged to be quite conservative [18]. It is indeed recognized that the frequency-domain passivity requirement often poses excessive limitations on performance. Examples of approaches violating the frequency-domain passivity requirement without limitations of coupled stability are time-domain passivity controllers [18], also implemented in teleoperation systems [19], and force-feedback controllers for wrist robots [20].

### *1.2. Inclusion of physical compliance for interaction control*

An alternative approach to improving the reflected dynamics of manipulators requires considerable changes to actuators design, as done in Series Elastic Actuators (SEA) [21,22], where a compliant element is introduced in series between the actuator and the load and its deflection measured. This measurement enables estimation of the interaction forces exchanged between the actuator and the environment, and ultimately of the interaction forces between the human and the robot.

SEAs were originally proposed for their mechanical advantages over stiff actuators, such as shock tolerance and increased power capabilities [21,23,24]. In later years, several research groups showed that Series Elastic Actuators can be successfully employed for accurate implementation of interaction control approaches with actuation systems that could not be modeled as low-impedance effort sources [25–27]. From a control perspective, the primary advantage of series elasticity over stiff force feedback is that the compliant force sensor reduces the physical gain of the feedforward path in the force control loop. In this way, the control gain can be proportionally increased to maintain the overall loop gain of the actuator, resulting in the same stability margins with higher control gains [22]. SEAs can then display a lower output impedance than the one of the actuator alone, without imposing the same stringent limits on the maximum reduction of endpoint inertia as is the case for systems with stiff force-feedback. In fact, this scheme allows simultaneous adoption of high-geared motors and achievement of low apparent load inertia, since motor inertia is decoupled from the load through the series elastic element.

Though the requirement on minimum reflected inertia for coupled stability does not apply to SEAs, it has been demonstrated that, if inner velocity loops are introduced in the control architecture, the SEA is not passive if it attempts to regulate a behavior corresponding to a pure spring with elastic constant higher than that of the physical compliant element [14]. In the following, we will refer to this case as "virtual stiffness control", in which it is desired to regulate the force of interaction $F_i$, in a way that it is proportional to the error between the measured position $x$ and a desired position $x_{des}$ through a constant $K_{des}$, named virtual stiffness, so that $F_i = K_{des}(x_{des} - x)$. Although different passivity conditions are obtained through alternative controllers types, the presence of inner velocity loops is often mandatory. This is certainly the case of non-backdrivable actuators which can be more suitably modeled in admittance causality, such as piezoelectric actuators. Practical examples of such velocity-sourced motors are ultrasonic piezoelectric motors, such as the one commercialized by Shinsei and utilized in MR-compatible robotics applications [28,29]. For this class of actuators, cascaded force–velocity represents the most direct implementation of an interaction controller. Unfortunately, the limit on passivity (achieved only for $K_{des} \leqslant k_s$) poses a stringent limitation on the maximum stiffness that can be accurately rendered through a compliant actuator that includes a non-backdrivable motor.

This paper investigates the consequences arising from the violation of the passivity requirement, when the actuated system is controlled to render a pure virtual stiffness with elastic constant higher than the physical spring of the SEA. The analysis is conducted for non-backdrivable motors that are modeled as ideal velocity sources, for which it is possible to derive the parameters of a stiffness compensator capable of achieving coupled stability with a wide range of passive environments. The approach is finally validated through both numerical simulations and experiments in a 1-DOF test bench.

## 2. Modeling and problem definition

The schematic of a SEA is presented in Fig. 1, in which an actuator drives the output mass through a spring-mass-damper system. The compliant actuator regulates the force of interaction with the environment $F_L$ through measurement of $x_M$ and $x_L$, representing motor and load displacements, respectively. Assuming knowledge