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# Passivity guaranteed stiffness control with multiple frequency band specifications for a cable-driven series elastic actuator

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Impedance control and specifically stiffness control are widely applied for physical human-robot interaction. The series elastic actuator (SEA) provides inherent compliance, safety and further benefits. This paper aims to improve the stiffness control performance of a cable-driven SEA. Existing impedance controllers were designed within the full frequency domain, though human-robot interaction commonly falls in the low frequency range. We enhance the stiffness rendering performance under formulated constrains of passivity, actuator limitation, disturbance attenuation, noise rejection at their specific frequency ranges. Firstly, we reformulate this multiple frequency-band optimization problem into the $H_\infty$ synthesis framework. Then, the performance goals are quantitatively characterized by respective restricted frequency-domain specifications as norm bounds. Further, a structured controller is directly synthesized to satisfy all the competing performance requirements. Both simulation and experimental results showed that the produced controller enabled good interaction performance for each desired stiffness varying from 0 to 1 times of the physical spring constant. Compared with the passivity-based PID method, the proposed $H_\infty$ synthesis method achieved more accurate and robust stiffness control performance with guaranteed passivity.

## 1. Introduction

Physical human-robot interaction (HRI) is of fundamental importance for robotic research and has been greatly advanced over the last two decades [1,2]. To improve interaction safety and obtain inherent compliance during physical HRI, the series elastic actuation (SEA) structure in which an elastic component is intentionally placed between the motor and load was proposed [3] and attracted continuous research efforts. The SEA provides a number of advantages over stiff actuation, including greater shock tolerance, more stable force output, lower reflected inertia, energy storage capacity and safety [3].

Various SEAs have been developed and applied for physical human-robot interaction, such as the Bowden-cable-based SEA for the lower extremity powered exoskeleton (LOPES) [4], the MR-compatible SEA for wrist sensorimotor study [5], the SEA for a monopod hopping robot [6], the compact SEA for upper and lower limb rehabilitation [7], the Bowden-cable SEA for hand finger exoskeleton [8–10], etc. The cable-driven SEA allows to detach the actuation motor from the robot frame, enables power transmission to remote place, and brings conveniences and flexibilities into system construction and control for applications to physical human-robot interaction [11–13].

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The robot is required to have the capability of varying its behavior from being stiff to compliant and even transparent for different interaction tasks. Impedance, defined by the dynamic relationship between the robot's output torque and motion, well characterizes the stiffness/compliance of the interaction. Impedance control that was proposed by Hogan in [14] has been a fundamental approach to shape the given system's behavior to match a predefined impedance model, and has been widely studied and applied in robotics [15–18].

In this work, we aim to shape the impedance that the robot exhibits to the human, or equivalently, the impedance that the human perceives when interacting with the robot. In this case, the motion in the designed impedance model is the active motion that the human applies to the robot, and the torque/force is the interactive torque/force between the human and robot.

Conventional impedance control approaches design the controller in a cascaded manner and lots of such control strategies with a PID-based inner force/torque loop have been employed for SEA [4,5,12,19–21]. Disturbance observer (DOB) based torque or impedance control strategies have also been proposed to improve SEA control accuracy and robustness [22–26]. Recently, adaptive torque or impedance controllers have been developed to guarantee predictable performance despite uncertainties or disturbance in the SEA or human side [27–32].

In [33–35], the SEA impedance control structure was transformed into the $H_\infty$ control framework. The impedance controller can be synthesized directly with minimizing the impedance rendering error. With a full comprehension of the practical system, the performance requirements and physical constraints of the system can be transformed to corresponding quantified norm bounds to each signal of interest [36].

Current SEA's impedance control results are obtained with full frequency-domain specifications (FFDSs). Considering that human movements only span the low band of the frequency domain, the frequency bandwidth requirement can be relaxed [37]. Besides, sensor noises appear at the high-frequency band. Therefore, restricted frequency-domain specifications (RFDSs) can be introduced into the impedance control to further enhance the performance at the specific frequency bands. There are methods that introduce filters or weighting functions into the impedance control framework to indirectly improve performance in certain frequency ranges [33–35]. However, there is no systematic method for design of a well-performed weighting function, and the weighting function needs to be incorporated into the augmented plant model, which increases the order of the synthesized controller. The generalized Kalman-Yakuboviv̆-Popov (KYP) lemma provided a possible approach to directly handle the RFDSs by converting it into equivalent linear matrix inequalities (LMIs), actually bilinear matrix inequalities (BMIs) [38]. But, the LMI-based approach runs into numerical difficulties due to the quadratic growth of the number of the Lyapunov variables. In [39,40], a non-smooth optimization technique was proposed to solve the fixed-structured controller synthesis problem with multiple models, multiple objectives and multiple frequency bands. With this method, it is possible to directly synthesize a fixed-order dynamic controller to achieve multiple frequency-domain specifications for the impedance control of the SEA.

However, stable torque control does not suffice for physical human-robot interaction, and the system has to guarantee passivity in the presence of uncertain contact dynamics [41]. In [4,5,20,21], a symbolic and analytical method with respect to the passivity constraints has been used to derive the allowable ranges of the control parameters for the PID based impedance control structure. However, this method can not directly give the desired controller gain, and the derived symbolic inequalities with respect to all the system's parameters are very complicated. Thus, it is not suitable for structured synthesis of the controller.

In our previous work [35], a mixed $H_2/H_\infty$ method based on a model matching framework was employed to synthesize the impedance controller with full frequency-domain specifications for a cable-driven SEA system. However, passivity could not be guaranteed.

In this paper, we address the stiffness control problem with restricted frequency-domain specifications of impedance rendering, passivity and robustness to improve the rendering performance for physical human-robot interaction with a cable-driven SEA. The main contributions of this paper lie in the following aspects. Firstly, this is the first work to formulate and realize impedance control of SEA with restricted frequency-domain specifications. Secondly, the strict passivity constraint can be guaranteed by transforming it into an equivalent norm bound over the entire frequency band. Then, a non-smooth optimization algorithm was adapted to find the solution and synthesize the controller.

The paper is organized as follows. The stiffness control problem for a cable-driven SEA and its $H_\infty$ synthesis framework are introduced in Section 2. Characterization of the restricted frequency-domain specifications, passivity transformation and controller synthesis are presented in Section 3. Extensive simulations, experiments, and results are shown in Section 4. Finally, Section 5 concludes the paper.

## 2. $H_\infty$ formulation of the stiffness control problem for a cable-driven SEA

### 2.1. Interaction with a cable-driven SEA

A cable-driven series elastic actuator used for interaction with a human hand is illustrated in Fig. 1. The cable for force transmission and a pair of linear springs are connected in series between the driving motor and the handle. When interacting with the cable-driven SEA, the human hand drives the handle to slide along the linear guide, while the motor rotates to regulate the spring deformation that produces force. Thus, the human hand perceives the generated impedance.