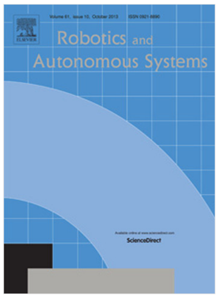
Accepted Manuscript



Impedance control of series elastic actuators based on well-defined force dynamics

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PII: S0921-8890(16)30325-6
DOI: http://dx.doi.org/10.1016/j.robot.2017.06.013
Reference: ROBOT 2875

To appear in: *Robotics and Autonomous Systems*

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Abstract—**Modern rehabilitation and assistive robots are usually designed with impedance-controlled compliant actuators. Impedance control is usually implemented based on an inner force loop which assumed to be very fast. Unfortunately force control performance can be influenced by the human dynamics leading to inaccurate impedance rendering. In our previous work we solved this force control issue by proposing a human-adaptive force controller which guarantees predictable performance in spite of uncertainties in the human. In this paper we propose a robustified human-adaptive control law and ensuring asymptotic stability instead of globally uniformly ultimately boundedness. Then, we analyze the application of human-adaptive force control on impedance rendering. We show (i) that impedance accuracy is improved with respect to standard solutions and (ii) that, leveraging on human-adaptive control, impedance accuracy may not need high bandwidth inner force control. Simulation and experimental results validate the proposed method and compare it with a widely used impedance control algorithm.**

Index Terms—**Impedance Control, Force Control, Series Elastic Actuators, Elastic Joints.**

I. Introduction

Assistive and rehabilitation robotics is a growing and promising frontier of robots development. In the past decades, the research and the investments in robotics were mainly addressed to industrial automation, where the interaction with humans was a marginal facet. In the near future, the need for robotic devices that will closely interact with humans is expected to dramatically increase. The demographic shift in world population is motivating a growing interest in human-assistive technologies and the recent investments of large companies, such as Honda, Toyota and Parker Hannifin, in anthropomorphic exoskeletal technologies represent a response to this need. Alongside with assistive technologies, medical robots are becoming mainstream products with large people acceptance, as in the case robot-assisted rehabilitation. Finally the investment of small and large robot producers, such as ABB, Kuka and Universal Robots, in human-cooperative robots, the so called "co-bots", is suggesting a pervasive interaction between robots and humans in the future.

This new generation of rehabilitation, assistive and cooperative robots is expected to show fundamental capabilities such as assistance as needed, safe cooperation with humans and soft interaction with unstructured environments. Nowadays, impedance control is the widely used tool to obtain these advanced features [1], [2], [3]. Instead of controlling robot position or forces, impedance control aims at shaping the dynamical relation between the two [4], [5], thus implicitly controlling the energy exchanged with the humans or the environment and prevent unsafe interactions. This allows to safely deal with all parts of a task including free motion, kinematically constrained motion, and dynamically constrained motion, as in the case of physical human-robot interaction (pHRI), where the environment is identified with a human.

Series elastic actuators (SEA's) represents another valuable tool for robot interaction control, allowing fine and stable force control of high power density motors. In fact, it has been shown that a series elasticity can guarantee higher stability robustness in force control [6], [7]. However, the high uncertainty in human and environment modeling is still posing challenges for control engineers: as shown in recent literature, it is still difficult to guarantee *well-defined* force control performance: when a robot interacts with a human (or environment), the human (or environment) dynamics enters in the plant, leading to uncertain performance. In particular, one may have slow force responses when the human displays a low mechanical impedance and force overshoots when the human is in a high impedance configuration. These effects are undesirable because they can generate disturbances that interfere with the assistive, rehabilitation or cooperation strategy. The literature recently reported a clear experimental evidence of this issue, showing how different load inertias can lead to different robot force performance [8]. We highlight that the importance of the environment (or human) dynamics in *explicit* force control [1] is historically recognized in the literature, regarding both stability and performance, as reported in the Whitney's seminal work [6]. In this light, some knowledge of the human (or environment) can significantly improve performance and stability robustness of *explicit* force control [10].

While robust stability of explicit force control has been often guaranteed using the passivity formalism [4], [11], solutions for robust performance are more recent and still in development. Several force control algorithms have been recently proposed based on robust control techniques, such as disturbance observers [12], [13], [8], [14], sliding-mode control [15], [16], [17] and adaptive control [18], [19], [20]. However most of these algorithms focus on robot-side uncertainties instead of human-side ones. Differently, we previously proposed a

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[1] According with [9], explicit force control regulates the force basing on a force sensor, by closing an artificial force feedback loop. Alternatively, implicit force control delivers forces in open loop by controlling the motor current. Implicit force control is intrinsically robust but requires low inertia and backdrivable actuators. According with the literature, explicit force control is more versatile and powerful (e.g. can reduce the apparent inertia and friction) but may suffer of stability issues. In the case of SEA's explicit force control is required to control the elastic dynamics e.g. to damp the resonance.