Optimal Mechanical/Control Design for Safe and Fast Robotics

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Abstract. The problem to ensure safety of performant robot arms during task execution was previously investigated by authors in [1], [2]. The problem can be approached by studying an optimal control policy, the “Safe Brachistocrones”, whose solutions are joint impedance trajectories coordinated with desired joint velocities. Transmission stiffness is chosen so as to achieve minimum–time task execution for the robot, while guaranteeing an intrinsic safety level in case of an unexpected collision between a link of the arm and a human operator. In this paper we extend this approach to more general classes of robot actuation systems, whereby other impedance parameters beside stiffness (such as e.g. joint damping and/or plasticity) can vary. We report on a rather extensive experimental campaign validating the proposed approach.

1 Introduction

In this paper we investigate the optimal design of mechanisms and controllers for safe and performant robotics, and propose an innovative solution based on mechanical actuator-transmission systems, that can vary their impedance parameters continuously during motion. In [1], [2] the authors introduced the idea of using a transmission system with varying stiffness, as a means of increasing the performance of the mechanism while satisfying safety constraints, and compared it with other existing approaches for guaranteeing safety and performance (e.g. [3]) by highlighting related potentialities and drawbacks. It should be pointed out that, while several mechanisms have been proposed in the robotics literature that can change transmission stiffness to adapt to different tasks (see e.g. [4], [5], [6]) the originality of our approach relies in dynamically controlling transmission characteristics within a single task.

The aim of this paper is to build upon the concept of variable stiffness and propose a more general class of Variable Impedance Actuators (VIA). Section 2 refers intuitively to the concept of Variable Impedance Approach. A brief highlight of Variable Damping and Variable Stiffness transmissions is reported respectively in section 3, and 4. Experimental results are reported showing the effectiveness of VIA in guaranteeing safety and performance during task execution.
2 Variable Impedance Approach for Guaranteed Safety and Performance

![Diagram](image)

**Fig. 1.** General design of the coupling between torque source and link for a manipulator impacting with human. $N$ denotes the reduction ratio, $I_R$ the axial rotor inertia; $I_L$ is the link inertia at the impact point; $K_e$ is the effective cover stiffness.

Consider the simple model in fig.1, describing a robot arm impacting with an operator, where $D_T$, $K_T$ are the damping and stiffness coefficients, respectively. Also let $N$ denote the transmission gear ratio. The mechanical impedance from the impact force $F$ to link velocity (relative to operator) $v_L$, $Z_m = \frac{F(s)}{v_L(s)}$ is given for this system by

$$Z_m = s \frac{(I_R N^2) I_L s^2 + [(I_R N^2) + I_L](D_T s + K_T)}{(I_R N^2)s^2 + D_T s + K_T}.$$  

The positive effect of small values of impedance parameters on safety is illustrated in fig.2. On the other hand, it can be expected that small impedance values affect negatively performance, by reducing the mechanical bandwidth of the transmission (see [1]). The method we propose to overcome this limit consists in dynamically varying the impedance parameters allowing fast task executions without affecting the safety level. The optimization method adopted to obtain the shape in which these parameters are to be varied with respect to a desired motion profile comply with what reported in [1] in case of a compliant transmission (see also fig.3), therefore it is not discussed in this paper.

The variable impedance actuation approach can be implemented acting on three different parameters, i.e. effective inertia (by e.g. changing the reduction ratio), damping, and compliance. Although the three parameters could in principle be varied simultaneously, we will explore in the next paragraphs only the variations of a single parameter at a time.

3 Variable Impedance Design

While in the previous section we introduced the concept of variable impedance as an effective means of dealing with the safety/performance trade-off, in this section we will review some examples of VI based mechanical implementations, so as to provide some background and directions to explore for the realization of novel intrinsically safe, efficient and compact actuation mechanisms for robotics.