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 Brachistocrone", 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 highligthing 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

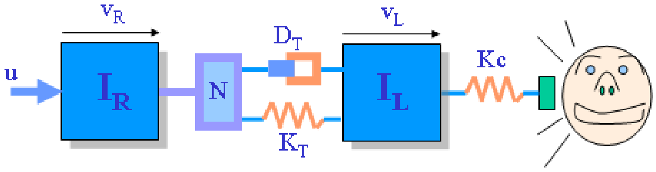

Fig. 1. General design of the coupling between torque source and link for a manipulator impacting with human. N denotes the reduction ratio, I_R the axial rotor inertia; I_L is the link inertia at the impact point; K_c is the effective cover stiffness.

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 reductiona 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 VIA 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.

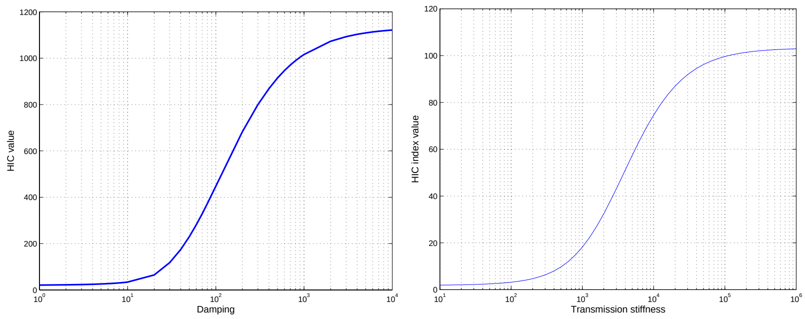

Fig. 2. Variation of the injury coefficient HIC (see e.g. [7], [1], [3]) for system in fig.1 with respect to impedance parameters, at constant link velocity $v = 2\,[m/s]$, and rotor and link inertias $M_{rot} = M_{link} = 1\,[Kg]$. As expected, in case of impact the injury risk increases with the coupling between the rotor and link.

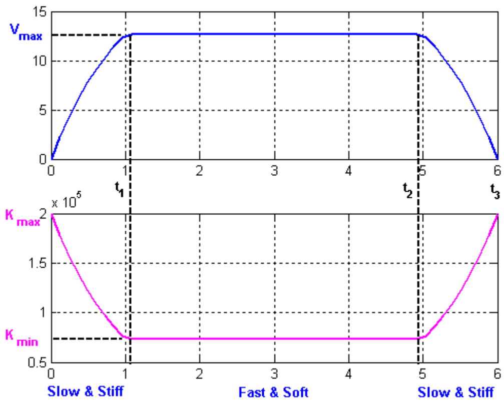

Fig. 3. Illustrating the intuitive behaviour of a Variable Stiffness Transmission in a 1DOF rest–to–rest task. High impedance is imposed at low velocities, while low impedance is used at high velocities to reduce potential impact injuries.

3.1 Variable Gear Ratio and Damping Transmissions

In order to change continuously the effective inertia $I_R N^2$, one could directly employ a variety of existing CVT (Continous Variable Transmission, [8]) mechanisms, many of which are readily commercially available. On the other hand, several possibilities for implementing actuators using the working principles of Magneto-Rheological (MR), Electro-Rheological (ER) Fluids, or Magnetic Particle Clutches (MPC's), are widely discussed in literature (see e.g. [9]). To implement a variable damping transmission, one could for example simply interpose a MPC, which is electrically controlled by a current I, between an actuator (such as an electric motor), and the

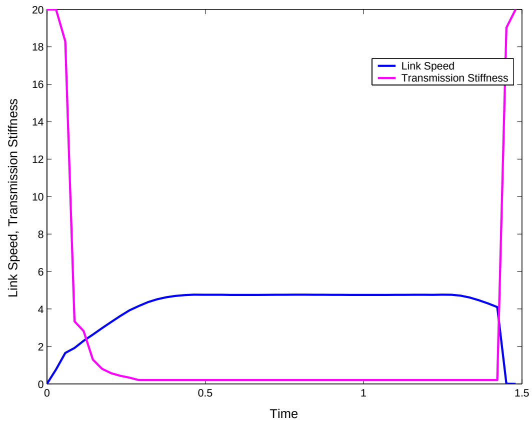

Fig. 4. The solution found with the Safe Brachistochrone algorithm for VDA. The minimum time optimal control sets high values of damping (i.e. impedance) for small values of speed and vice versa.

joint. In this manner, as the current increases, the damping factor $D(I)$ between the main shaft and joint velocities changes continuously (albeit nonlinearly) from a minimum to a maximum coupling. In the early stage of the VDT control design we adopted the Safe Brachistochrone to obtain results which can be used as a starting point for controlling the transmission damping in case of safety–oriented and perfomant manipulators (see fig. 4). As a matter of fact, results obtained by simulation comply with intuition in fig.3. Although actual implementation of VIA by either variable gear ratio or damping can be readily conceived by the above or other devices, preliminary experimentation has shown some limitations of commercially available devices (CVT's and MPC's), with particular regard to response time and nonlinearities, which hindered so far further experimenal validation. While the investigation is continuing on these solutions, in the following we provide more details on devices implementing continuous adaptation of impedance through variable stiffness transmissions (VST).

3.2 Variable Stiffness Transmission

A direct way to implement a Variable Stiffness Transmission (VST) is to design it with antagonistic configuration of nonlinear actuators, such as e.g. by interposing nonlinear spring–like mechanisms between at least two motors and the actuated joint [10]. In fact, a very important characteristic of these transmissions is that it is relatively simple to vary independently the equilibrium position q of joint shaft and transmission stiffness $\sigma(q, \theta_1, \theta_2)$ by suitably controlling the positions θ_1, θ_2 of motor shafts (see fig.5). Practically speaking, it can be highlighted that motions $\delta\theta_1 = -\delta\theta_2 = \delta\theta_\sigma$ of the motor shafts generate stiffness variations $\delta\sigma = \sigma(\delta\theta_\sigma)$,

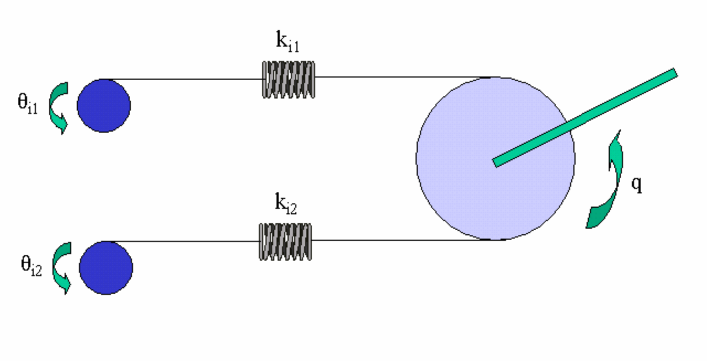

Fig. 5. Appearance of an antagonistic VST actuation system for the $i-th$ joint of a robot arm. The action of the two motors θ_{i1}, θ_{i2} generates a compression or a decompression of springs with nonlinear elasticities k_{i1}, k_{i2}, allowing the independent variation of joint positions q, and transmission stiffnesses $\sigma(q, \theta_{i1}, \theta_{i2})$.

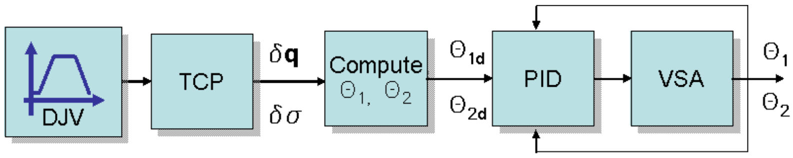

Fig. 6. VSA Control System. Desired main shaft positions θ_{1d}, θ_{2d} are chosen accordingly to (1) where $\delta\sigma$ is computed by the Trajectory Compliance Planner (TCP, [2]) so as to guarantee safety during motion with respect to a desired pre–planned joint velocity (DJV).

while motions $\delta\theta_1 = \delta\theta_2 = \delta\theta_q$ generate only joint angular displacements (in equlibrium configurations). This implies two equations

$$\begin{cases} \delta q = \frac{\delta\theta_1 + \delta\theta_2}{2} \\ \delta\sigma = \sigma(\frac{\delta\theta_1 - \delta\theta_2}{2}), \end{cases}$$

which can be solved, if σ is an invertible function, to find the desired angular displacements of the motors

$$\begin{cases} \delta\theta_1 = \delta q + \sigma^{-1}(\delta\sigma) \\ \delta\theta_2 = \delta q - \sigma^{-1}(\delta\sigma). \end{cases} \quad (1)$$

In fig.6 it is reported a control scheme that can be implemented to control a Variable Stiffness Actuator (VSA), or a more general VST. A rotary VSA developed in our lab is described in fig.7. With the VSA we obtained experimental trajectory–tracking results which comply with the solutions of the Safe Brachistochrone applied in case of a compliant transmission (see fig.8). Experimental results are also reported in fig.9 showing the effective variation of transmission stiffness for VSA.

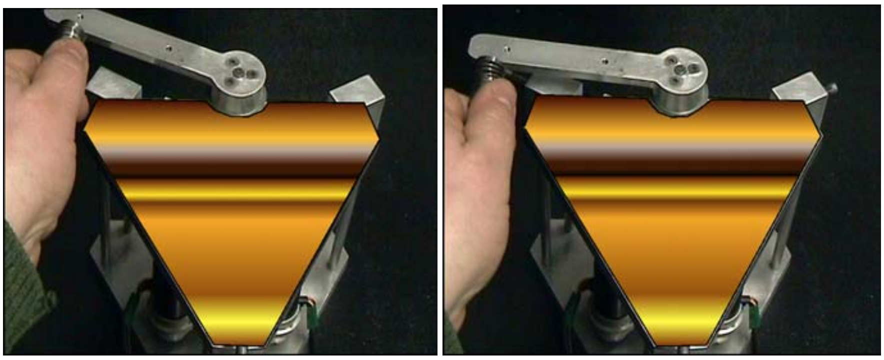

Fig. 7. The VSA developed at the Centro Interdipartimentale di Ricerca "E. Piaggio". The actuator is designed to allow the independent control of joint shaft position and stiffness (see the VSA in compliant (*left*) and stiff (*right*) configurations).

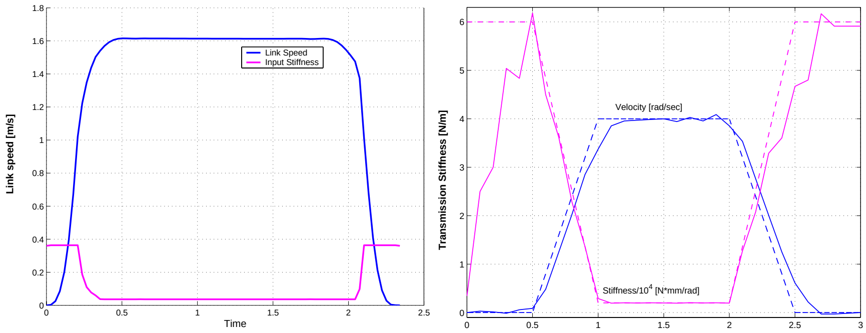

Fig. 8. Results of the Safe Brachistochrone applied to a variable compliant transmission (*left*), and joint speed and stiffness trackings results for the VSA during motion (*right*)

In the next paragraph we report some results of experiments we performed to test during motion the effectiveness of VSA, and of the VIA in general, in guaranteeing safety during a rest-to-rest motion task.

3.3 Safety guaranteed through VIA motion

The setup we realized to perform impact experiment with VSA is simply constituted by the VSA and a rotary accelerometer (see fig.10). A lightweight link, rigidly connected to the VSA joint shaft, impacts with the accelerometer during motion at different transmission stiffnesses σ. The measured acceleration $a(t)$ (see for instance fig.11) is then used to compute the relative HIC

$$HIC = \Delta T \left(\frac{1}{\Delta T} \int_{\Delta T} a(t) dt \right)^{2.5}$$

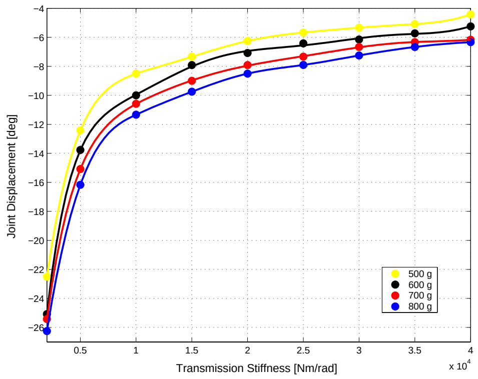

Fig. 9. Experimental displacement of the joint shaft of the VSA with respect to the transmission stiffness at increasing values of the applied axial load (from *yellow* to *blue*).

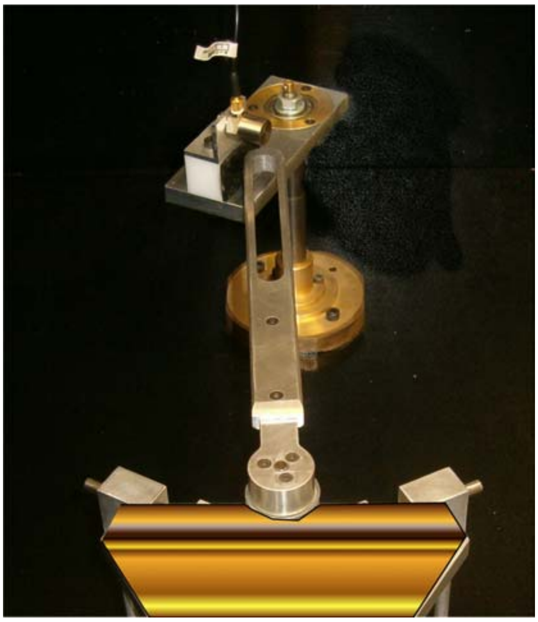

Fig. 10. Experimental setup for impact experiments with VSA.

where ΔT is the time duration of the impact. At this stage, it is be interesting to note how both ΔT and the maximum $a(t)$ *decrease* and *increase* with σ respectively. This behaviours generate variations of the injury risk. In fig.12 the experimental HIC curves for the VSA during motion at different transmission stiffness and velocity

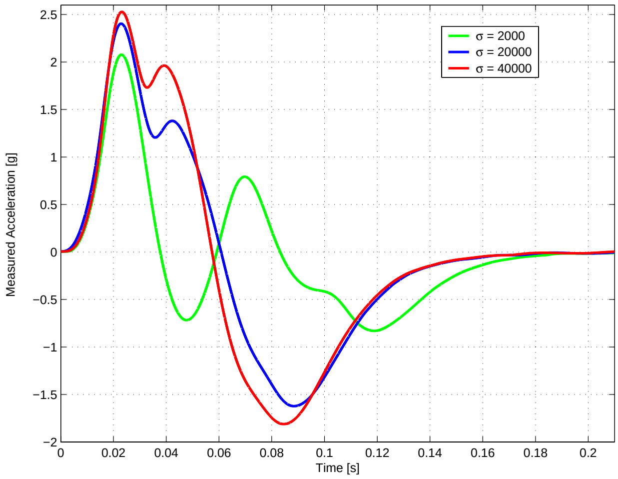

Fig. 11. Samples of the acceleration measured after collision at different stiffnesses of the VSA transmission, and at constant link velocity $v = 9\,[rad/sec]$.

(shaft velocity increases from *blue* to *green*) highlight how performance is limited due to safety constraints.

Such results suggest interesting hints for VIA control schemes. In particular, it shows that it is possible to set the higher impedance during motion until the safety bound is reached, and after that it is necessary to vary impedance parameters with respect to the link velocity, in a manner in which both maximum acceptable level of HIC and performance are preserved (see also the results of the Safe Brachistochrone problem reported in fig.8). In other words, the TCP in fig.6 chooses the trajectory $\sigma(HIC, DJV)$ to be followed by the VSA transmission stiffness, which ensures the desired HIC bound never be trespassed during the task execution. An example of experimental TCP output for a particular rest-to-rest velocity task, and safety bound $HIC = 75$, is reported in fig.13(*Left*). This output was used to control the VSA so as to perform impact experiments reported in fig.13(*Right*), from which the effectiveness of the proposed VSA in guaranteeing the safety bound during a trajectory traking task appears clearly.

4 Conclusion

The problem of achieving high performance with a mechanism which is safe to humans interacting directly with it poses many challenging technological problems. After a brief explanation of our concept of safety and performance for a robotic system, in this paper we have introduced, and experimentally validated, the concept of VIA that allow fast and accurate operation of a robot arm while guaranteeing a maximum suitable level of injury risk.

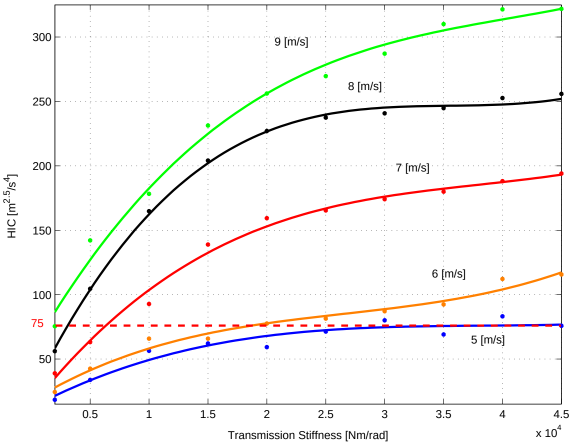

Fig. 12. Experimental results of the injury risk in case of impact at different tranmsission stiffnesses for VSA. As expected, the maximum allowable velocity v of the joint shaft decreases as the value of transmission stiffness σ increases, if an acceptable level of injury risk is chosen (as e.g the *red dashed* straight line, corresponding to $HIC = 75$). Continuous lines represent the fourth order minimum square interpolation of the experimental data (*dots*).

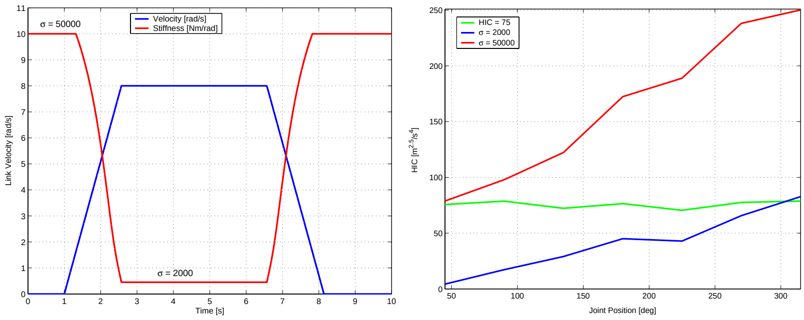

Fig. 13. (*Left*) Output of the TCP for a desired joint velocity at constant safety bound $HIC = 75$. The desired stiffness trajectory is obtained by interpolation of results in fig.12. (*Right*) Impact results in case of rigid (*red*), compliant (*blue*), and VIA (*green*) transmissions related to the accelerating phase of the task.

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