Safe and Fast Actuators for Machines Interacting with Humans

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Abstract— **This paper describes a new generation of actuators for robotic applications, and more generally for machines that are designed to interact with humans. Such actuators, called Variable Impedance Actuators, are designed to achieve fast motion control while guaranteeing safety of human operators in worst-case impact situation. The fundamental innovation is to implement safety by purely mechanical, passive means, to guarantee intrinsic safety, while active control is used to recover performance. The design concept, which is the subject of a patent application, has led to the experimental implementation of a Variable Stiffness Actuator. The effectiveness of the VSA has been recently validated theoretically and experimentally by authors [1].**

Keywords— **Human–Machine Interaction, Actuators, Safety, Performance, Variable Impedance, Controllable Stiffness.**
IP Info.— **Patent number: The VIA concept and mechanisms described in this paper are currently being processed for patent by the Italian Patent Office.**

I. Introduction

Machines that interact with humans must be safe against all possible accidents. Taking this for granted, the second most important goal is their performance - which can be often expressed in terms of velocity of motion. A machine that moves fast is typically more dangerous than a slow-moving machine, but slow machines are often unacceptable in applications.

Some attempt have been made in the past to overcome this problem by using sensorization of the moving parts of the machine, and active control. These solution tend to be costly, encumbrant, and not sufficiently reliable.

The purpose of the device presented in this paper is to enable the construction of safe and fast machines, at a low price, and with intrinsic, purely mechanical built-in safety means.

A new mechanical/control co–design approach, the Variable Impedance Approach (VIA), has been recently introduced by authors [1] as a new way to guarantee safety and performance during task executions for a robot arm. Briefly, this approach relies on the possibility to vary the mechanical impedance (i.e. stiffness, damping and/or gear–ratio parameters) of the actuation subsystem in a way that guarantees mechanical safety during fast motions. This general concept can be implemented by different mechanisms. In this paper a new class of compact rotary actuators with variable and controllable joint shaft stiffness is illustrated, along with experimental results performed with a prototype VSA highlighting the effectiveness of VIA to guarantee safety during execution of fast trajectory tracking tasks.

II. Working Principle of VSA

The main characteristic of a VSA is to mechanically decouple the rotary inertia of the torque source (e.g. DC–Motors) from the inertia of the actuated joint shaft by varying the mechanical impedance of the transmission. Transmission impedance is comprised of several parameters, including stiffness, damping, and gear ratio. We focus here on Variable Stiffness Transmission (se also [2] for some possible implementations of the VST concept).

A compact and reliable actuator realizing the VST concept is reported in fig. 1–*Left*. The actuator consists ot two independently controlled brushless DC motors, which are connected to the joint shaft by a timing belt. The belt is tensioned by means of three idle pulleys, connected to the casing by passive elastic elements (see fig. 1–*Right*).

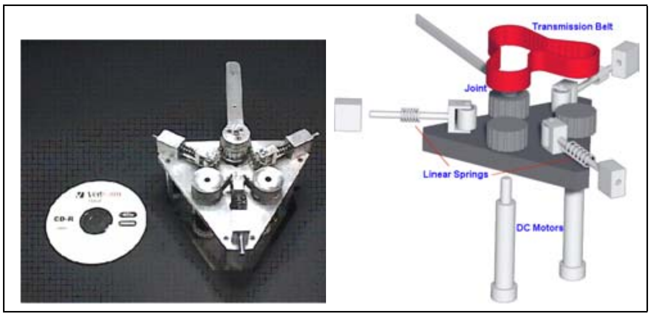

Fig. 1. A prototype of Variable Stiffness Actuator.

The core of the VSA is its torque transmission system (see fig. 2), that allows to control independently joint shaft positions and stiffness by opportunely varying the angular displacements q_1, q_2 of the DC–Motors during task executions (see fig. 3).

Next section is devoted to show experimental results performed with a laboratory prototype of the VSA. These experiments highlight the effectiveness of VIA to allow safe and performant motions.

III. Safety Aspects of VSA

The primary aim of VSA is to change in Real–Time transmission stiffness during motion of the joint shaft in a manner that guarantees low levels of injury indexes (such

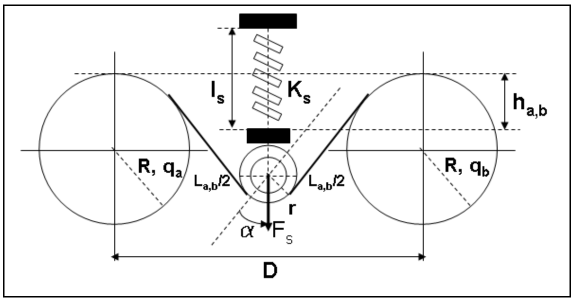

Fig. 2. Particular of the VSA's torque transmission system. Transmission stiffness σ changes non–linearly during motion with the active length $h_{a,b}$ of the springs K_s.

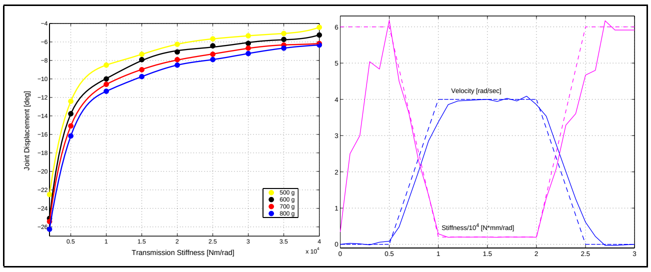

Fig. 3. (*Left*) Joint shaft displacements (y axis) at increasing both transmission stiffness (x axis) and axial payload (from *yellow* to *blue*) for VSA. (*Right*) Joint shaft position and stiffness trajectory tracking for VSA. Desired joint shaft stiffnesses are chosen in Real–Time with optimal control policies in a manner that guarantees minimum levels of injury risk during tasks execution [1].

e.g. the HIC [3], that is adopted in the automotive industry).

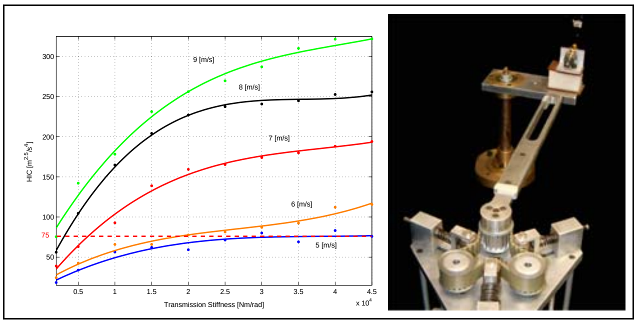

Fig. 4. (*Left*) Experimental results of impacts between the VSA and a rotary accelerometer (*Right*).

In fig. 4, experimental results of simulated impacts with VSA show that HIC is a monotonically increasing function on both velocity v and stiffness σ of the joint shaft. That implies it is possible to perform fast trajectory tracking tasks at bounded HIC (e.g. $HIC_{max} = 75$ in figure) by opportunely varying transmission stiffness with respect to the velocity of the joint shaft (see fig. 3 – Right). Experimental HIC results, performed during the accelerating phase of a fast pick–and–place task, are reported in fig. 5.

In this case desired stiffness trajectories for VSA are chosen adopting optimal control tools, accordingly to what reported in [1]. These results highlight how the possibility to adapt the transmission stiffness to the different phases of a task is advantageous and preferable to having fixed-compliance transmission, either highly compliant (hence slow) or rigid (but unsafe).

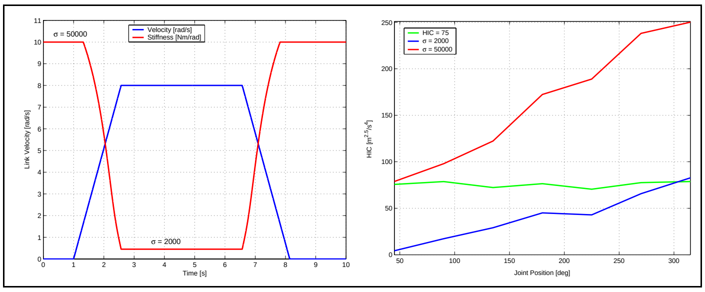

Fig. 5. (*Left*) Trajectories in both stiffness and velocity of the joint shaft obtained by using the optimality control tools reported in [1].(*Right*) Experimental HIC results for compliant (*blue*), rigid (*red*) and VSA (*green*) transmissions during the accelerating phase of the task.

IV. Market Survey

Although we did not perform an exhaustive interview campaign, some preliminary contacts with industry representatives have indicated that possible applications of the VSA concepts are primarily where machines are designed to physically interact with humans, such as:

- human-friendly robotics and automation
- rehabilitation devices
- body-exercise and training machines
- entertainment machines (theme and amusement parks)
- haptic interfaces

V. Conclusions

In this paper, a class of actuators with variable mechanical stiffness is proposed. The possibility to vary stiffness during motion is a useful way to guarantee low levels of injury risk during execution of fast trajectory tracking tasks. That implies the possibility to adopt these actuators to realize fast and safe mechanisms for robotic applications, in particular those which imply a close cooperation with humans. The proposed mechanism can be assembled compactly and with low costs.

References

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