Variable Stiffness Actuators for Fast and Safe Motion Control

Antonio Bicchi[1], Giovanni Tonietti[1], Michele Bavaro[1], and Marco Piccigallo[1]

Centro Interdipartimentale di Ricerca
"E. Piaggio"
Università di Pisa
http://www.piaggio.ccii.unipi.it

Abstract. In this paper we propose Variable Stiffness actuation [1] as a viable mechanical/control co–design approach for guaranteeing control performance for robot arms that are inherently safe to humans in their environment. A new actuator under development in our Lab is then proposed, which incorporate the possibility to vary transmission stiffness during motion execution, thus allowing substantial motion speed-up while maintaining low injury risk levels.

1 Introduction

A robot arm that is to interact with humans has a single design consideration at a premium, that is safety. Under no circumstances should the robot arm cause harm to people in its surroundings, directly nor indirectly, in regular operation nor in failures. Having this stated, the second most crucial requirement on robot manipulators remains with their performance, i.e., broadly speaking, in their accuracy and rapidity in performing tasks when required. This paper will report on different possible approaches at dealing with the problem of achieving the best performance, under the condition that safety is guaranteed throughout task execution.

Safety of robots involve several different considerations and depend on many factors, ranging from software dependability, to possible mechanical failures, to human errors in interfacing with the machine, etc.. A thorough hazard analysis and risk evaluation should be performed according to methodical procedures specifically for different domains of application: these methods are receiving a growing attention from both the scientific community (e.g. [2–4]) and international standardisation bodies (see for instance [5]). General hazard management considerations are very broad, of course, and fall beyond the scope of the present paper. Here, we will only consider a specific, if very important, type of risk: the situation in which, in an unspecified instant during execution of a pre-planned robot arm movement, a collision between a link of the arm and a human occurs. The quantitative analysis of the trade-off between such risk, and the performance obtainable, is one of the objectives of our work. Such analysis has a strong impact on how robot mechanisms and controllers should be designed for human-interactive applications, giving rise to a paradigm shift in robot design, which we will argument in detail.

In this paper, we first provide a discussion of the intrinsic limits of performance imposed by safety constraints. Achievable tradeoffs are illustrated with reference

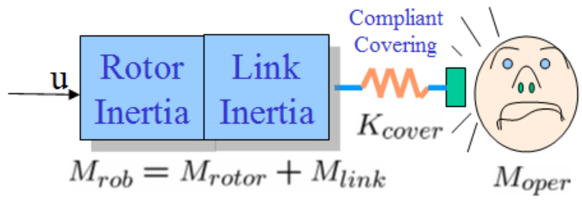

Fig. 1. Simplified model of the impact between a rigid 1DOF robot arm and an operator.

to different compliant joint actuation schemes, including passive elastic joints, the Distributed Macro-Mini (DM^2) actuation scheme ([6]), and Variable Stiffness (VS) transmission [1]. Limits of performance under safety-enforcing constraints for these schemes are compared. Based on this analysis, the Variable Stiffness Transmission is considered as a candidate technology for high-performance, intrinsically safe mechanism design.

2 Limits of Performance Under Safety Constraints

To lay down a principled discussion of different joint actuation schemes in terms of safety and performance, it is important to establish quantitative definitions of both these concepts. In the following paragraphs we will give definitions which attempt at not being too restrictive, although of course full generality can not be hoped for with any formula for such faceted concepts.

2.1 Safety and Performance

As already stated in the introduction, we will only focus on a particular aspect of safety of robot manipulators, which is against unexpected collisions by the manipulator with a human operator. Researchers have developed several standard indices of injury severity, including e.g. the Gadd Severity Index (GSI), and his mathematical refinement Head Injury Criterion (HIC) [7] introduced firstly in robotics by [6],

$$\mathrm{HIC} = T\left[\frac{1}{T}\int_0^T a(\tau)d\tau\right]^{2.5}$$

where T is conventionally the final time of impact and a is the acceleration of the head of the operator during the impact.

In general, evaluation of the above severity indices is numeric, based on either experimental or simulated data. However, it is instructive to compute the most widely used index, the HIC, for the basic case of a single rigid joint moving at uniform velocity v before impact, as depicted in fig. 1. In this case, by integration of the equations of motion and simple calculations, one gets

$$
\begin{aligned}
&\text{HIC} = 2\left(\tfrac{2}{\pi}\right)^{\frac{3}{2}}\left(\tfrac{K_{cov}}{M_{oper}}\right)^{\frac{3}{4}}\left(\tfrac{M_{rob}}{M_{rob}+M_{oper}}\right)^{\frac{7}{4}} v^{\frac{5}{2}} \\
&:= \beta(M_{rob}, M_{oper}, K_{cov}) v^{\frac{5}{2}}.
\end{aligned} \tag{1}
$$

where in particular the effective mass $M_{rob} = M_{rotor} + M_{link}$ accounts for both the reflected rotor inertia and link inertia at the impacting section. Notice that $\beta(\cdot) > 0$ is a function only of mechanical (inertial and compliance) parameters: hence, imposing a maximum acceptable level of injury risk at HIC_{max} implies an upper bound on the link velocity

$$
v_{safe} = \left(\frac{HIC_{max}}{\beta(\cdot)}\right)^{\frac{2}{5}}. \tag{2}
$$

Using data of the second link of a lightweight arm in our lab ($M_{rot} = 1.2\ Kg$, $M_{link} = 0.1\ Kg$, soft rubber cover compliance $K_{cov} = 5\ KN/m$, and $M_{oper} = 4\ Kg$), we have that an acceptable HIC of 100 would imply a velocity upper limit $v_{safe} \simeq 2\ m/s$.

The second crucial step is to quantitatively define performance, or rather *a* performance metric, so that we can make informed design and control decisions. Among many aspects of performance associated with servo-controlled mechanisms such as robot arms, a primary concern is promptness of response, as it is e.g. classically measured in the response to a step input. Clearly, answers to such questions as "How long does it take to bring the arm from rest to rest at a prescribed position?" depend clearly on two factors: the mechanical design and the adopted control law. To our purposes, it is important that we decouple the mechanical and the control design problems. This can be done if an "absolute enough" performance measure is adopted, which abstracts away the possible controller choices in this phase, allowing one to concentrate on the intrinsic properties of the mechanism. In other terms, we should like to use the *best possible controller* with all different mechanisms we are interested in examining, and compare their performance in such ideal conditions.

A measure of how fast a given mechanism can be brought to a desired configuration, under limited acuator authority and with safety guarantees, but with an ideally smart control, is its *safe brachistochrone*, that is the solution to the following problem:

> For a mechanism with total inertia and actuator limits given, find the minimum time necessary to move between two fixed configurations, such that at any instant during the motion, an unexpected impact with the device would produce a injury severity index below safety levels.

Such problem formulation lends itself to a direct interpretation in terms of a *minimum time optimal control* problem. For instance, the safe brachistochrone for the basic case of fig. 1, with bounded actuator torque $u \leq U_{max}$, can be written mathematically as

$$\begin{cases} \min_T \int_0^T 1 \, dt \\ M_{rob}\ddot{x}_{rob} = u \\ |\dot{x}_{rob}| \leq v_{safe} \\ |u| \leq U_{max} \end{cases} \tag{3}$$

with initial and terminal conditions equal to zero. In this case, an explicit solution for the optimal control can be obtained analytically by application of Pontryagin's Maximum Principle [8,9]. The relationship thus obtained between performance (minimum time to reach the origin) and the acceptable level of injury risk is reported in fig. 2, which shows how performance is inevitably degraded by imposing increasingly high safety constraints. It is important to note that to recover minimum-time performance, only mechanical design changes can be effective, as the control resources are exhausted by optimal control. Assuming that total link inertia is minimized, and that covering compliance cannot be further increased, a possibility for performance enhancement is left with the design of non-rigid mechanical transmission.

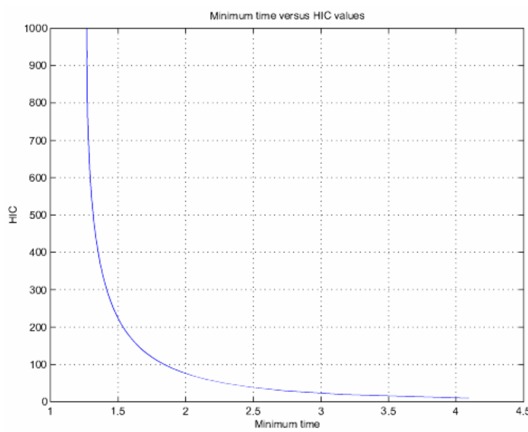

Fig. 2. The safety-performance tradeoff curve for the rigid single joint case.

2.2 The Safe Brachistochrone for a compliant transmission

While several different approaches have been proposed for the mechanical design of inherently safe arms, the vast majority has in common the use of elastic joints. The basic idea behind the purposeful introduction of compliance in the joint transmission is that of decoupling the inertia of the actuator proper (which is very relevant, especially for geared actuators) from the inertia of the link. The achieved decoupling is dynamic, and acts stronger at high frequencies, thus smoothing out the impact force curve and reducing potential danger. The positive effect of transmission elasticity

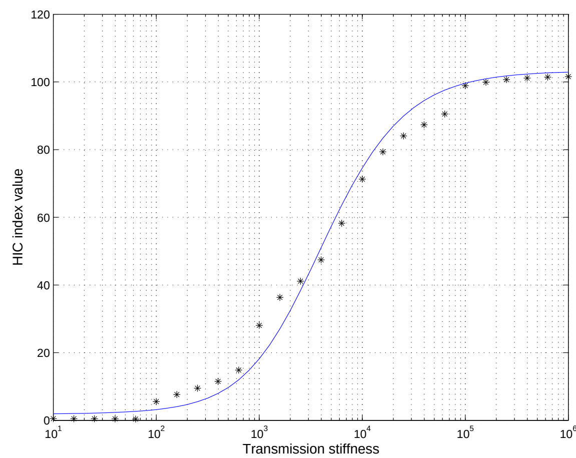

Fig. 3. Head Injury Coefficients evaluated for the impact of a link of effective inertia $M_{link} = 0.1\ Kg$ elastically coupled to a rotor of inertia $M_{rot} = 1.2\ Kg$ by a transmission with $B_{transm} = 0$, as K_{transm} varies. The rotor and link are assumed to move uniformly at velocity $v = 10\ m/s$ before impact.

on safety is illustrated in fig. 3, where the HIC of the impact between an elastically actuated link moving at uniform velocity and an operator is reported at varying the transmission stiffness K_{transm}. Note explicitly that, in the limit $K_{transm} \to \infty$, the HIC tends to the value obtained by (1) in the rigid link case, while, for $K_{transm} \to 0$, only the link inertia M_{link} is relevant to HIC. HIC data in fig. 3 are obtained via accurate numeric integration of the equations of motion after impact.

The downside of elastic coupling is clearly performance degradation. The problem of controlling passively elastic joints so as to recover performance has been studied at length in the robotics literature, both in the general case (see e.g. [10,11] and the review in [12]) and in safety-oriented design contexts (e.g [13]). The safe brachistochrone problem can be posed in this case as

$$\begin{cases} \min_T \int_0^T 1\ dt \\ M_{rot}\ddot{x}_{rot} + K_{transm}(x_{rot} - x_{link}) = u \\ M_{link}\ddot{x}_{link} + K_{transm}(x_{link} - x_{rot}) = 0 \\ |\dot{x}_{link}| \leq v_{safe}(K_{transm}) \\ |u| \leq U_{max} \end{cases}$$

with initial and terminal conditions equal to zero. Here, the safety constraint has been imposed by limiting the impacting link velocity such that the admissible level of injury risk is never trespassed in the execution of motion. The safe brachistochrone for an elastic joint can be found by numerical methods such as those described in [9]. Results reported in fig. 4 show how the shortest time to reach a given goal is a function of the joint elasticity. The performance, considered as the inverse of such minimum time, is low for high stiffness, as the high reflected inertia forces in this case

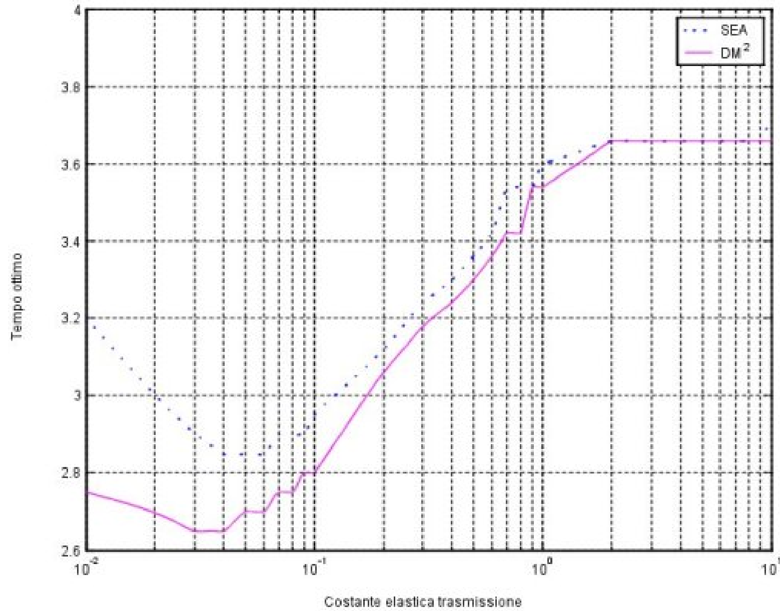

Fig. 4. Minimum time to goal under safety constraints and actuator saturation, as a function of the elastic coupling stiffness, for a passive elastic joint (dashed) and for a DM^2 actuation scheme.

very low maximum velocities. On the other hand, too low a transmission stiffness is not beneficial to performance either, because of the limited mechanical bandwidth. The diagram in fig. 4 indicates an optimum value of transmission stiffness (for the given inertial parameters), whereby the best performance within safety bounds is achieved.

3 Performance Recovering

As already argued, although several techniques have been devised to efficiently control elastic-joint arms, the intrinsic performance limitation (illustrated by the safe brachistochrone) can only be overcome by modifying the mechanical design and introducing a somewhat more complicated actuation mechanism. Two concepts have been recently proposed in this context: the Distributed Macro-Mini (DM^2) actuation [6] and the Variable Stiffness transmission [1] approaches.

DM^2 mainly consists in dividing torque generation among two actuators, of which one is devoted to low-frequency components of the required torque supply, while the other is designed for the high frequency part. The two motors are connected in parallel to the same joint: the slow one, which provides high torque at the cost of large rotor inertia, is coupled through a passive elastic transmission; the fast

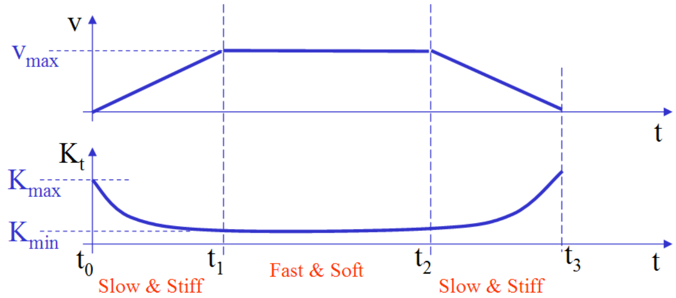

Fig. 5. Illustrating the intuitive behaviour of a Variable Stiffness Transmission in a 1DOF rest–to–rest task. High stiffness is imposed at low velocities, while transmission compliance is introduced at high velocities to reduce potential impact injuries.

motor, with limited torque but very low rotor inertia, is rigidly connected to the joint. The safe brachistochrone for the DM^2 actuation scheme for different values of the coupling stiffness, computed numerically ([9]), is reported in fig. 4.

A different approach to gain in performance for guaranteed-safety joint actuation schemes has been firstly proposed in [1], and consists in allowing the passive compliance of transmission to vary during the execution of tasks.
While we will show in a later section an example on how such variation of stiffness could be implemented, we present here the basic working principle. Consider the classical velocity profile for the actuation of a rest-to-rest motion of a joint (fig. 5), consisting of an initial ramp accelerating from zero to maximum velocity, a uniform velocity part, and a final descending ramp decelerating again to zero. At a rather intuitive level, it would be desirable that the joint had low stiffness in the high velocity phase, so as to minimize reflected inertia and thus injury risks. On the other hand, it would seem appropriate to have as high a stiffness as possible in the early accelerating phase, so as to allow the actuator to put the link in motion swiftly, and in the final deceleration, where oscillations have to be minimized. The solution of the safe brachistocrone for the VS scheme proves indeed that such intuition is correct, as shown by the numerically evaluated optimal profiles of velocity and compliance reported in fig. 6. The performance of the VS scheme can overcome even that of DM^2, as shown in fig. 7, provided that the transmission stiffness can be varied in a large enough range. The VS approach is clearly closer in inspiration to biological muscular apparatuses than to classical machine-tool design, which has inspired most robotic design thus far. Although several projects have being pursued in research labs towards the design of passively compliant arms (see e.g. [14]), most of the proposed schemes can only preset a joint stiffness to a desired value before executing a task. The VS approach is innovative in that it changes compliance continuously and in real time, while executing the motion task.

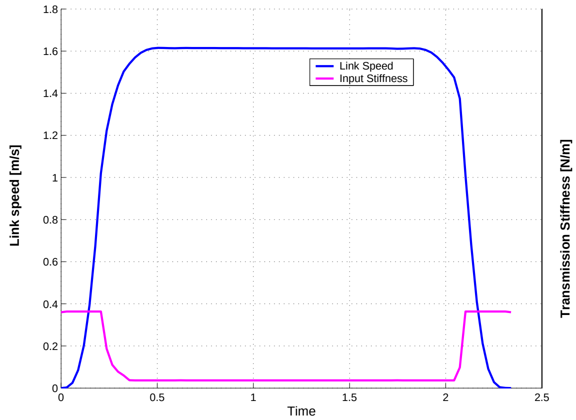

Fig. 6. Optimal joint stiffness and velocity during a rest–to–rest task under safety constraints, as obtained by a numerical solution to the safe brachistochrone of a VS actuator.

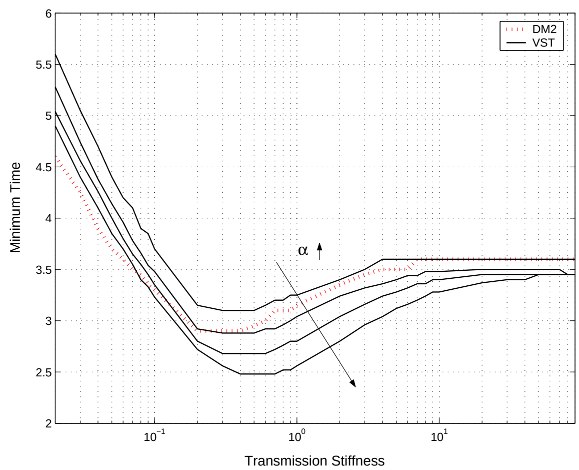

Fig. 7. Results of the safe brachistochrone for both VS transmission (*black*) and DM^2 (*red*) schemes, as a function of the stiffness center value $\bar{\sigma}$ and for different stiffness ranges Δ_σ. It is noteworthy that as large is the range of stiffness allowed for VS transmission, as large is the performance recovering (row means that Δ_σ increases for constant $\bar{\sigma}$).

4 A new Variable Stiffness Actuator

The Variable Stiffness approach is a conceptual framework wich allows for a wide variety of implementations, including e.g. double effect pneumatic cylinders, non linear springs, McKibben's artificial muscles, etc. ([15]).

In this paper, we present a novel design of a VS actuator developed at our lab,

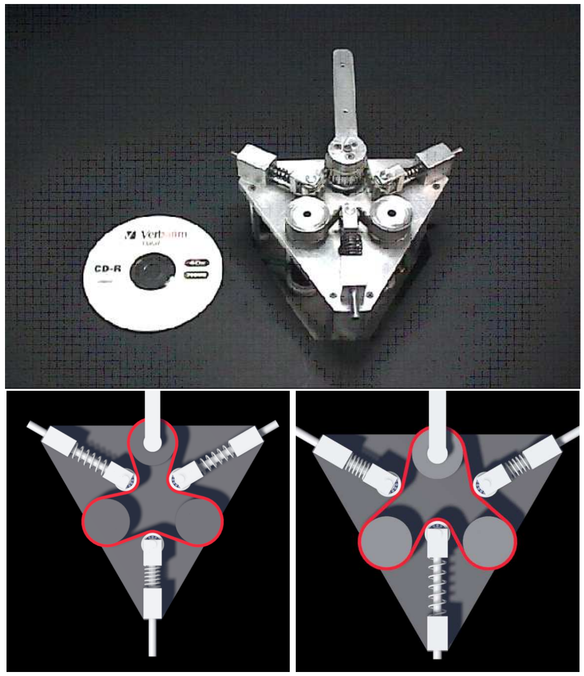

Fig. 8. (*top*)Appearance of the prototype VS actuator being developed at Centro “E. Piaggio”, University of Pisa. (*bottom*) The VS actuator in compliant (left) and stiff (right) configuration.

which is intended for compact implementation (fig. 8). The actuator consists of two independently controlled motors (of the brushless type in this implementation), which are connected to the joint by a timing belt. The belt is tensioned by means of three idle pulleys, connected to the casing by passive elastic elements.

5 Conclusion

The problem of achieving high performance with a mechanism which is safe to humans interacting directly with it poses many challenging technological problems. In this paper we have considered the problem of designing joint actuation mechanisms that may allow fast and accurate operation of a robot arm while guaranteeing a suitably limited level of injury risk. Among few different possible schemes it is shown that Variable Stiffness is the one that allows potential performance. Finally, we briefly reported a new actuator that is currently under study in our Lab for performing experiments with Variable Stiffness transmission.

Acknowledgments

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