# Optimization and Fail–Safety Analysis of Antagonistic Actuation for pHRI

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**Summary.** In this paper we consider some questions in the design of actuators for physical Human-Robot Interaction (pHRI) under strict safety requirements in all circumstances, including unexpected impacts and HW/SW failures.

We present the design and optimization of agonistic-antagonistic actuation systems realizing the concept of variable impedance actuation (VIA). With respect to previous results in the literature, in this paper we consider a realistic physical model of antagonistic systems, and include the analysis of the effects of cross–coupling between actuators.

We show that antagonistic systems compare well with other possible approaches in terms of the achievable performance while guaranteeing limited risks of impacts. Antagonistic actuation systems however are more complex in both hardware and software than other schemes. Issues are therefore raised, as to fault tolerance and fail safety of different actuation schemes. In this paper, we analyze these issues and show that the antagonistic implementation of the VIA concept fares very well under these regards also.

## 1 Introduction

One of the goals of contemporary robotics research is to realize systems which operate with delicacy in environments they share with humans, ensuring their safety despite any adverse circumstance [4]. These may include unexpected impacts, faults of the mechanical structure, sensors, or actuators, crashes or malfunctional behaviours of the control software [6, 7, 1, 5].

A recent trend in robotics is to design *intrinsically safe* robot arms by introducing compliance at their joints. The basic idea of this approach is that compliant elements interposed between motors and moving links help prevent the (heavy) reflected inertia of actuators from concurring to damage in case of impacts. Introducing compliance, on the other hand, tends to reduce performance of the arm. Some approaches in the direction of minimizing the perfor-

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mance loss while guaranteeing safety in case of impacts have been presented in the recent literature (see e.g. [2]). Among these, a method was proposed in [2] consisting in varying the compliance of the joint transmission mechanism while moving the arm. This so-called Variable Stiffness Transmission (VST) technique, and its generalization in the Variable Impedance Actuation (VIA) concept, have been shown to be capable in theory of delivering better performance than purely passive compliance and other techniques.

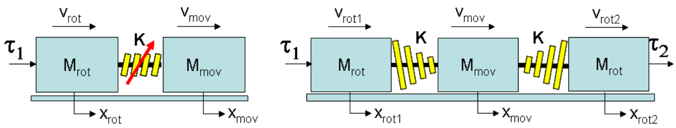
In its formulation, however, the VIA concept in [2] used a rather abstract model of actuator and transmission, whereby the impedance could be directly controlled to desired values in negligible time. In this paper, we consider a more realistic model of an actuation system implementing the idea, which is based on the use of two actuators and nonlinear elastic elements in antagonistic arrangement. The antagonistic solution has several advantages, and has been used in many robotic devices before (see e.g. [3, 11, 14, 13, 8]), in some cases because of biomorphic inspiration. However, to the best of our knowledge the introduction of nonlinear springs to achieve variable stiffness in real time (i.e., during different phases of each motion act) was not a motivation for earlier work with the purpose of guaranteeing safety.

In this paper, we consider the implementation of the VIA concept by means of antagonistic actuation, discuss the role of cross-coupling between antagonist actuators, and apply optimization methods to choose parameters which are crucial in its design. We show that antagonistic systems can implement effectively the VIA concept, and their performance compares well with other possible approaches.

Antagonistic actuation systems however are more complex in both hardware and software than other schemes. Issues are therefore raised as to whether safety is guaranteed under different possible failure modes. In the paper, we also analyze these issues and show that the antagonistic implementation of the VIA concept fares very well under these regards also.

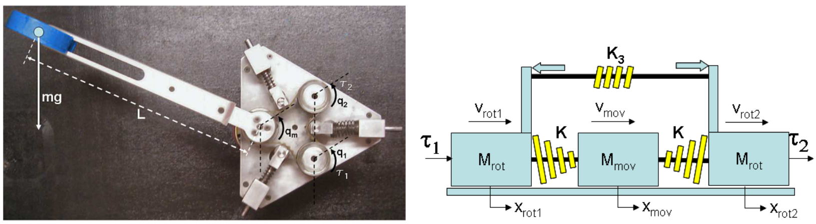
## 2 Antagonistic Actuation as a VIA System

In [2] it was shown that an ideal VIA mechanism (depicted in fig. 1-a) can effectively recover performance of mechanisms designed to guarantee safety of humans in case of impact. The basic idea is that a VIA mechanism can be controlled according to a *stiff-and-slow/fast-and-soft* paradigm: namely, to be rather stiff in the initial and final phases of motion, when accuracy is needed and velocity is low, while choosing higher compliance in the intermediate, high-velocity phase, where accuracy is typically not important. Low stiffness implies that the inertia of the rotors does not immediately reflect on the link in case of impacts, thus allowing smoother and less damaging impacts. Such arguments were supported in [2] by a detailed mechanism/control co-design optimization analysis, based on the solution of the so-called *safe brachistochrone*




a) b)

**Fig. 1.** The concept of Variable Impedance Actuation (a) and a possible implementation by means of antagonistic actuators (b). Effective rotor inertias are coupled to the link inertia through nonlinear springs.




a) b)

**Fig. 2.** An experimental implementation of an antagonistic VIA actuator (a) and its conceptual scheme (b).

problem, i.e. a minimum time control problem with constraints on the maximum acceptable safety risk at impacts. The model considered fig. 1-a, however, uses direct variations of impedance, which is not physically realizable. A possible implementation of the concept via an antagonistic mechanism is depicted in fig. 1-b. Practical implementations of antagonistic VIA systems may assume more general configurations than the one in fig. 1-b. For instance, in the prototype of an antagonistic VIA system depicted in fig. 2-a ([10]), the two actuators act through a nonlinear elastic element on the link, but they are also connected to a third elastic element cross-coupling the actuators.

Questions we consider in this section are the following: is the stiff-and-slow/fast-and-soft control paradigm still valid, and are the good safety and performance properties of the ideal VIA device fig. 1-a retained by an antagonistic implementation as in fig. 1-b? What is the role of cross-coupling elastic elements as in fig. 2-b in antagonistic VIA actuators?

To answer these questions, we use again the analysis of solutions to the safe brachistochrone problem, which consists in finding the optimal motor torques $\tau_1, \tau_2$ which drive the link position $x_{mov}$ between two given configurations in minimal time, subject to the mechanism's dynamics, motor torque limits, and safety constraints. This problem is formalized for the antagonistic mechanism of fig. 1-b as

$$\begin{cases} \min_{\tau} \int_0^T 1 \; dt \\ M_{rot1}\ddot{x}_{rot1} + \phi_1(x_{rot1}, x_{mov}) = \tau_1 \\ M_{rot2}\ddot{x}_{rot2} - \phi_2(x_{rot2}, x_{mov}) = \tau_2 \\ M_{mov}\ddot{x}_{link} - \phi_2(x_{rot2}, x_{mov}) - \phi_1(x_{rot1}, x_{mov}) = 0 \\ |\tau_1| \leq U_{1,max} \\ |\tau_2| \leq U_{2,max} \\ HIC(\dot{x}_{mov}, \dot{x}_{rot1}, \dot{x}_{rot2}, \phi_1, \phi_2) \leq HIC_{max}, \end{cases} \tag{1}$$

where $M_{mov}$, $M_{rot1}$, $M_{rot2}$ are the inertias of the link and the rotors (effective, i.e. multiplied by the squared gear ratio); $U_{i,max}, i = 1, 2$ is the maximum torque for motor $i$; $\phi_i$, $i = 1, 2$ represent the impedance of deformable elements as functions of the position of the rotors and link. A polynomial nonlinear stiffness model is used, whereby the applied force as a function of end-point displacement is

$$\phi_i(x_j, x_k) = K_1(x_j - x_k) + K_2(x_j - x_k)^3. \tag{2}$$

This model has been found to fit well experimental data for the device in fig. 2-a.

The safety constraint $HIC(\dot{x}_{mov}, \dot{x}_{rot1}, \dot{x}_{rot2}, \phi_1, \phi_2) \leq HIC_{max}$ describes the fact that the *Head Injury Coefficient* of an hypothetical impact at any instant during motion, should be limited. The *HIC* is an empirical measure of biological damage used in car crash analysis literature ([12]), and depends on both the velocity of the impacting mass, its inertia and the effective inertia of rotors reflected through the transmission stiffness. The *HIC* function is rather complex, and can only be evaluated numerically for non trivial cases. However, based on simulation studies, a conservative approximation of the *HIC* function for the antagonistic mechanisms was obtained which allows rewriting the safety constraint in the simpler form $|\dot{x}_{mov}| \leq v_{safe}(\phi_1, \phi_2, HIC_{max})$ (cf. [2]).

Different solutions of problem (1) have been obtained numerically, setting parameters to realistic values as $M_{mov} = 0.1$ Kgm$^2$, $M_{rot1} = M_{rot2} = 0.6$ Kgm$^2$, $HIC_{max} = 100 \frac{\text{m}^{2.5}}{\text{s}^4}$, $U_{1,max} = U_{2,max} = 7.5$ Nm.

A first interesting set of results is reported in fig. 3. The optimal profiles of link velocity and joint stiffness are reported for the case where both the initial and final configurations are required to be stiff ($\sigma_0 = \sigma_f = 16$ Nm/rad, plots a and b) and when both are compliant ($\sigma_0 = \sigma_f = 0.2$ Nm/rad, plots c and d). Notice in fig. 3 that the stiff-and-slow/fast-and-soft paradigm applies also to antagonistic actuation approaches. The minimum time necessary in the two cases is 2.4 sec and 2.65 sec, respectively. This level of performance should be compared with what can be achieved by a simpler actuation system, consisting of a single actuator connected to the link through a linear elastic element (this arrangement is sometimes referred to as SEA, Series Elastic Actuation [9]). A SEA system with a motor capable of torque $U_{max} = 2U_{1,max} = 15$ Nm and inertia $M_{rot} = 2M_{rot1} = 1.2$ Kgm$^2$, with linear elasticity coefficient matched exactly with the required stiffness in the two cases $\sigma = 16$ and $\sigma = 0.2$, would

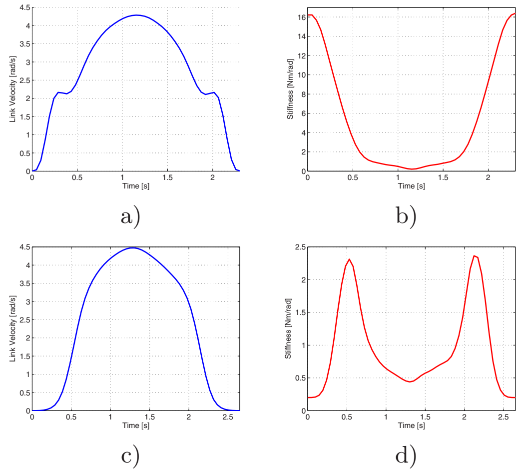


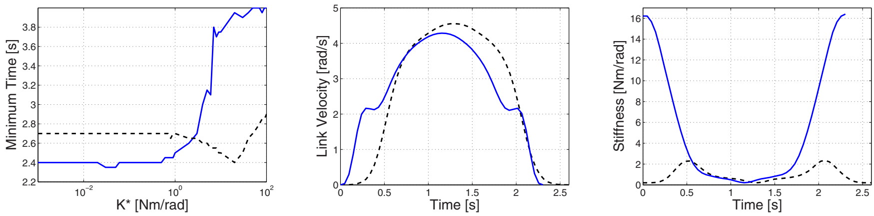

**Fig. 3.** Optimization results for antagonistic actuation without cross-coupling in a pick-and-place task. A stiff-to-stiff task is shown in a, b, while c, d, refer to a soft-to-soft task.

reach the desired configuration in 3.15 sec and 3.6 sec, respectively. Moreover, it should be pointed out that the SEA system cannot change its stiffness without modifying the mechanical hardware.

Focusing again on the antagonistic VIA system's results, it is also interesting to notice that, in the likely case that the task requires the manipulator to be stiff at the initial and final configurations (as it would happen e.g. in a precision pick-and-place task), the actuators are required to use a significant portion of their maximum torque just to set such stiffness, by co–contracting the elastic elements. However, it is also in the initial and final phases that torque should be made available for achieving fastest acceleration of the link.

Based on this observation, it can be conjectured that some level of preloading of the nonlinear elastic elements in an antagonistic VIA system could be beneficial to performance. Elastic cross-coupling between actuators (fig. 2-b) can have a positive effect in that it can bias the link stiffness at rest, so that more torque is available in slow phases, while torque is used for softening the link in fast motion. On the other hand, it is intuitive that very stiff cross-coupling elements would drastically reduce the capability of the mechanism to vary link stiffness, thus imposing low velocities for safety and ultimately a performance loss.

It is therefore interesting to study the effect of cross-coupling, to determine if there is an intermediate value of stiffness which enhances performance with respect to the limit cases of fig. 1 (no cross-coupling) and constant stiffness (rigid cross-coupling). To this purpose, we study a modified formulation of the safe brachistochrone problem, namely




a) b) c)

**Fig. 4.** a) Minimum time to reach the target configuration vs. cross-coupling stiffness $K_3$ ($L_0 = 1$). Solid: $\sigma_0 = \sigma_f = 16$ Nm/rad; dashed: $\sigma_0 = \sigma_f = 0.2$ Nm/rad. Optimization results for antagonistic actuation with cross-coupling in a pick-and-place, stiff-to-stiff task (solid) and soft-to-soft task (dashed): velocity (b) and joint stiffness (c).

$$\begin{cases} \min_\tau \int_0^T 1\ dt \\ M_{rot1}\ddot{x}_{rot1} + \phi_1(x_{rot1}, x_{mov}) - \phi_3(x_{rot1}, x_{rot2}) = \tau_1 \\ M_{rot2}\ddot{x}_{rot2} + \phi_2(x_{rot2}, x_{mov}) + \phi_3(x_{rot1}, x_{rot2}) = \tau_2 \\ M_{mov}\ddot{x}_{link} + \phi_2(x_{rot2}, x_{mov}) - \phi_1(x_{rot1}, x_{mov}) = 0 \\ |\tau_1| \le U_{1,max} \\ |\tau_2| \le U_{2,max} \\ HIC(\dot{x}_{mov}, \dot{x}_{rot1}, \dot{x}_{rot2}, \phi_1, \phi_2) \le HIC_{max}, \end{cases} \tag{3}$$

where $\phi_3(x_{rot1}, x_{rot2})$ indicates the cross-coupling elasticity. In particular, we study how optimal solutions vary in different instances of the problem with increasing cross-coupling stiffness. A linear stiffness model is assumed for cross-coupling, with $\phi_3(x_{rot1}, x_{rot2}) = K_3(L_0 + x_{rot2} - x_{rot1})$, where $L_0$ denotes the preload offset.

In fig. 4 numerical solutions obtained for problem (3) are reported, for the two stiff-to-stiff and soft-to-soft tasks already considered in fig. 3).

It can be observed from fig. 4-a that an optimal value of cross-coupling $K_3$ exists in both cases, but they do not coincide. Setting for instance $K_3 = 0.04$ Nm/rad, the optimal value for the stiff-to-stiff task, we obtain the optimal link velocity and stiffness plots reported in fig. 4-b and -c, and the optimal times 2.35 sec and 2.65 sec, respectively. Optimizing the design for one task can hence decrease performance in others.

## 3 Fail Safety

In this section we analyze how antagonistic VIA mechanisms behave under failure of some of their components, and compare their ability to remain safe in spite of failures, with those of other possible actuation structures.

A large variety of possible failure modes should be considered in order to assess fail safety of a robot system. In our case, we focus on the following possible events: mechanical failures, consisting in breakage of one or more of the elastic elements, leading to $K \to 0$, and HW/SW control failures, whereby one or more of the actuators delivers an uncontrolled torque. In the latter case, we consider that the torque can either remain "stuck" at some value, or default to zero, or to $\pm U_{max}$.

An extensive simulation campaign has been undertaken to study the effective HIC at impacts of an antagonistic VIA mechanism (fig. 1-b), evaluating all possible failure mode combinations. To be conservative, the HIC is evaluated assuming an impact occurs after some time from the instant of the fault event, during which time the mechanism could increase its momentum. The diagram in fig. 5 reports the worst-case HIC during the execution of a typical pick-and-place task, under a nominal optimal control. Labels in different regions indicate which failure mode determines the worst-case HIC of impacts. It can be noticed from fig. 5 that the worst case impact has maxi-

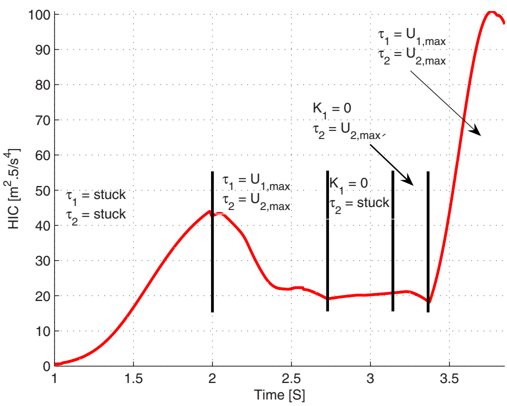



**Fig. 5.** HIC values under different failures mode for VIA.

mum HIC value around 100. This has been obtained by suitably choosing the mechanism parameters, in particular by setting $U_{1,max} = U_{,2max} = 1.5Nm$. The performance under these design choice is around 3 sec. Should different values of worst-case HIC be specified, the antagonistic VIA mechanism could be designed with different parameters to accommodate for the specifications.

It is interesting to compare these results with other existing actuation systems for pHRI. Namely, we will make reference to SEA and to the so-called Distributed Macro-Mini ($DM^2$) actuation scheme ([15]). The latter basically consists of a SEA with a small inertia, low torque, high bandwidth actuator connected directly to the link inertia to actively damp oscillations.

In order to obtain a meaningful comparison, we consider optimized SEA and $DM^2$ implementations, with equal rotor and link inertia, which obtain a similar performance of 3 sec in the same task. Fig. 6 describes the worst-case HIC values obtained for SEA and DM$^2$, respectively. Failure modes have been considered which are analogous to those described above, as are all other parameters in the simulations. It can be observed that, in some modes (notably for control torques defaulting to their maximum value, $\tau \rightarrow U_{max}$), both SEA and DM$^2$ are not as safe as VIA (HIC $\gg$ 100). The DM$^2$ scheme exhibits slightly better fail safety characteristics than SEA. An explanation of the apparently superior fail-safety characteristics of antagonistic VIA actuation is that such scheme achieves comparable nominal performance by employing two motors each of much smaller size than what necessary in the SEA and DM$^2$.

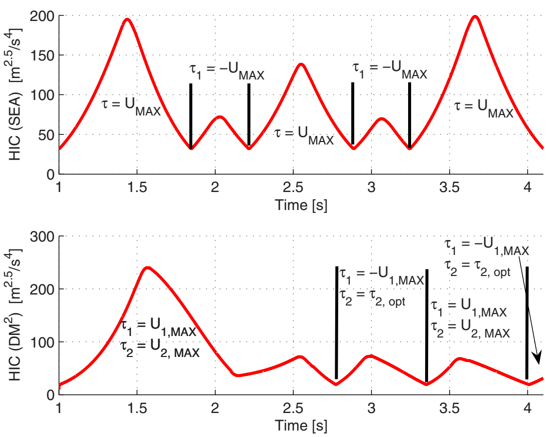



**Fig. 6.** Maximum of the HIC value in various failure cases for SEA (top) and DM$^2$ (bottom).

## 4 Conclusion

We discussed the design of variable stiffness actuation systems based on antagonistic arrangements of nonlinear elastic elements and motors. The basic stiff-and-slow/fast-and-soft idea of the VIA approach was shown to apply and to be effective for realistic models of antagonistic actuation for a single joint. However, a VIA mechanism assembly can sometimes become heavy for practical purposes to be implemented in a serial link robot. It may be advantageous to use the actuators at base instead of respective joints, and motion can be transferred to joints via transmissions, where, the transmission element itself can be designed to have nonlinear stiffness, for example in a tendon driven system.

In order for the system to guarantee safety of operations in the proximity of humans, its behaviour must remain safe in conditions where functionality is degraded by possible failures. A thorough examination of possible HW and SW failures of the system has been considered, and results have been compared with those of other possible solutions, with favourable result.

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