Variable Impedance Actuations for Physical Human Cooperating Robots: a Comparative Analysis of Performance, Safety and Dependability

Roberto Filippini, Soumen Sen and Antonio Bicchi*

***Abstract*— An antagonistic actuation with variable stiffness is proposed for ensuring safety and performance in human friendly robotic applications. Various arrangements are analysed with respect to performance, safety and dependability. The results are expected to provide useful guidelines for choosing an actuation mechanism and its implementation for human-robot interactive applications.**

I. Introduction

Safety in robotics is obtained by applying compliance at the joints, thus reducing the reflected actuator inertia at the link, which plays decisive role in case of accidental impacts. Techniques like Variable Stiffness Actuation (VSA) and its generalization Variable Impedance Actuation (VIA) apply such approaches [2]. The compliant system results safer though a certain reduction of performance is likely to be expected. A balance of the two quantities, safety and performance, is obtained in [2], [6] through the solution of an optimal control problem, the safe brachistochrone. The safe brachistochrone generates the optimal trajectory of the link under strict safety constraints. The control paradigm of stiff-and-slow/soft-and-fast operation takes place: to be stiff in the initial and final phases of motion, when accuracy is needed and velocity is low, and compliant (soft) in the intermediate, high-velocity phase, where accuracy is not important.

This paper deals with a 1-dof system of VSA under safe brachistochrone control. Various antagonistic arrangements are proposed, each consisting of two prime movers with interconnections using non-linear and linear springs as transmission elements. A fault management system is considered for supervising the functioning and treating failures in a safe way either by recovering the system or stopping the operation.

Studies of performance, safety and dependability are conducted for the proposed arrangements of the actuation system. First simulations are carried out to obtain the best parameter settings for the assumed task. Few faulty scenarios are analysed with the aim of discovering if the system turns to be unsafe, therefore demanding for additional measures, like fault management. Safety is quantified in term of consequences due to impact, borrowing the HIC metric used in automotive industry [7]. Failure scenarios are deduced from a failure modes and effects analysis (FMEA). The study of system dependability is modeled in a state transition diagram representing the degradation caused by the same failures as identified by FMEA ([1], [4]). Two dependability attributes are considered: i) the reliability, which is the probability that the system is able to control stiffness and steer the joint, and ii) the survivability, which is the probability the system is able to continue operation at an acceptable reduced performance. Results from the diverse analyses are expected to provide a wider cross section of the system with the aim of evaluating which arrangement meets the best balance.

* Authors are at the Interdepartmental Research Centre "E.Piaggio", The University of Pisa, 56126 Pisa, Italy. bicchi@ing.unipi.it

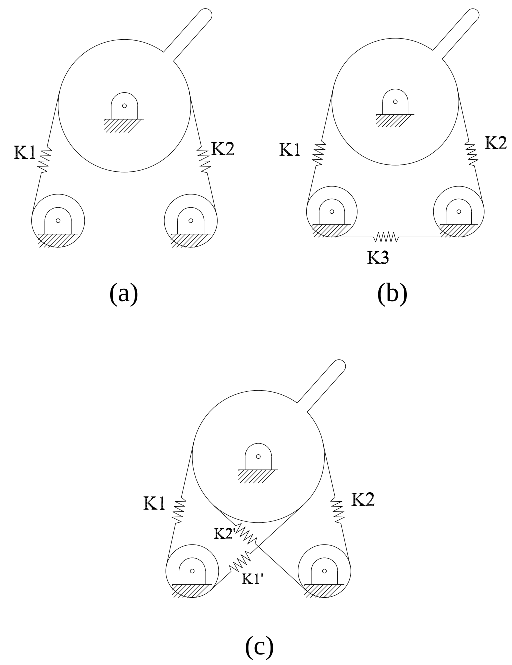


Fig. 1. (a) The simple antagonistic arrangement , (b) the arrangement with cross-coupling and (c) the bi-directional.

II. System description and optimization

The schematics of the three arrangements of the actuation system are shown in Fig. 1, while Fig 2 shows the realization of one of them, the cross-coupled. Two antagonistically posed prime movers (DC motors) provide the necessary force for the motion, transmitted via linear/non-linear transmission elements. The simple AA consists of two identical non-linear springs, K_1 and K_2. The cross-coupled adds a third linear spring K_3 between the motor joints, which pre-loads the system in the rest position. The bi-directional has two extra linear springs K_1' and K_2', one per side, with pre-loading and two steering directions per actuator.

Fig. 2. The cross-coupled arrangement (Robotic Lab, Centro Piaggio, Pisa)

The safe brachistochrone problem is formulated for each of the three arrangements. The objective function is the time to accomplish the task from the initial state (initial position = 0, speed = 0, initial stiffness) to a final state (final position = 2π, speed = 0, final stiffness = initial stiffness), under constraints on *safety* and the maximum rated voltage of the motor. The task consists of one anti-clockwise revolution, from stiff to stiff. The safety constraint is set to HIC = 10. The *safe brachistocrone* returns the optimal control inputs (the voltages) at the motors, and different simulations are performed in order to find the best values for the spring elements.

A sample of results for the simple AA is shown in Figure 4. High velocity is reached for a low stiffness at the link joint. The HIC value tends to reach the maximum and the stiff-and-slow and the fast-and-soft behaviour is clearly manifested. Similar results are obtained for the other arrangements. A more complex design does not necessarily return a better performance.

III. Fault management and dependability issues

A failure modes and effects analysis have been carried out for the three arrangements and few of these have been reproduced during a simulated run of the system. The VSA is an open loop control law, so that any fault is very likely the cause of a wrong trajectory of the link and possible concerns for safety. This is attested by simulations of a motor failure (fail saturated) and the breakage of the pulling spring. In both cases, the system misses the desired final state and also increases the HIC along the run above the limit, which makes it to not to be intrinsically fail-safe. Recovery of safety being mandatory for human-robot applications, additional measures have to be considered to manage faults when they occur and recover the system to a functioning safe state [8]. The fault management considered for the presented case studied is specified with its functional interface. The system monitors any state change in the actuation mechanism and triggers reconfigurations for adjusting controls and recovering from the faulty operational scenario [5]. A first reconfiguration (R1) deals with faults for which it is still possible to apply VSA controls. A second reconfiguration (R2) is foreseen in case of loss of one steering direction or the stiffness control, for which it becomes impossible to apply VSA and controls are switched into non-VSA mode. In case the failure is not recoverable or the reconfiguration has failed, another level of protection exists: to abort the operation.

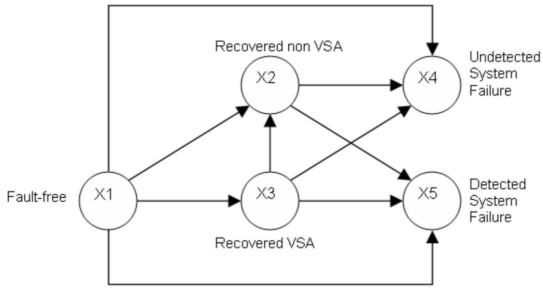


Fig. 3. The general state transition diagram.

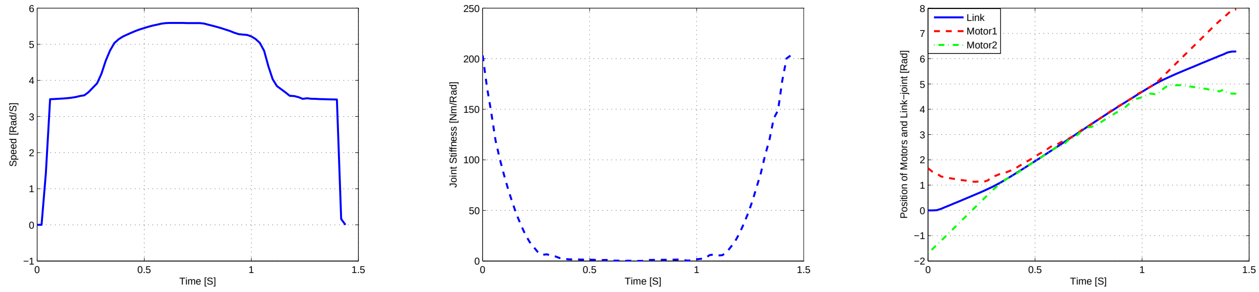
The fault management govern the state changes in the finite set X, which are initiated by a fault. For the considered actuation systems, five (macro)states have been identified:

1) (X1) Fault free: the system applies the optimal VSA,
2) (X2) Recovered VSA: the system applies VSA after successful reconfiguration,
3) (X3) Recovered non-VSA: the system applies a non-VSA control after successful reconfiguration,
4) (X4) Detected system failure: stop of operation,
5) (X5) Undetected system failure: the system has failed in operation.

The general state transition diagram is shown in Figure 3. To make the model more realistic, the fault management reconfiguration R1 and R2 and the fail stop (FS) are assigned a coverage C. The coverage is a value between 0 and 1, with C = 1 if the fault treatment (from the detection to the reconfiguration) is always successful, and C less than 1 if there is a probability that the fault is missed. For example the successful fail-stop due to a missing reconfiguration R1 is calculated as $(1 - C1)C3$.

The system dependability attributes of interest are reliability and survivability. The reliability $R(t)$ is the probability of being in X1 or X2. The system survivability $Sv(t)$ is the probability of being reliable or in X3.

The general model of Figure 3 is specialized for the three arrangements. The time to failure of each component is assumed to be exponentially distributed. The resulting stochastic process is a Continuous Time Markov Chain (CTMC) [4], described by the Kolmogorov equations, which return the probability distribution $\mathbf{p}(t) = [p_1(t), p_2(t), p_3(t), p_4(t), p_5(t)]$ in X, for the initial state $\mathbf{p}(t) = [1, 0, \ldots, 0]$ at t = 0. The various CTMC are analysed for a dataset of failure rates, all assumed to be equal to 10^{-5}/h, and three operational scenarios: i) only fail stop ii) fail stop and R1 and iii) fail stop, R1 and R2. Instead of reliability and survivability, their average statistics Mean Time To Failure $MTTF = \int_0^\infty R(t)dt$ and Mean Time To Survive Failure $MTTSF = \int_0^\infty Sv(t)dt$ are calculated.



(a) (b) (c)

Fig. 4. Optimal operation of simple AA. (a) Link-joint speed, (b) Link-joint stiffness and (c) Motors and Link-joint positions.

TABLE I

MTTF AND MTTSF (IN YEARS) FOR THE ACTUATION ARRANGEMENTS VERSUS DIFFERENT SETTINGS OF THE FAULT MANAGEMENT SYSTEM.

	FS		FS and R1		FS and R1 and R2	
	MTTF	MTTSF	MTTF	MTTSF	MTTF	MTTSF
Simple AA	2.8	2.8	2.8	2.8	2.8	2.8
Cross-coupled AA	2.3	2.3	2.8	2.8	2.8	4
Bi-directional AA	1.9	1.9	2.8	2.8	2.8	6

Results (in years) are shown in Table I. With the only fail stop facility, the simplest arrangement results the most reliable one with $MTTF$ = 2.85 years. If reconfiguration R1 is added, the three systems behave identically, no distinction existing between reliability and survivability. If reconfiguration R2 is also included, the effect of fault management turns to be effective to survivability for the bi-directional and the cross-coupled. The $MTTSF$ increases to 6 years and 4 years for the bi-directional and the cross-coupled respectively, while it is 2.85 years for the simple arrangement. In the latest modeled scenario, the complexity in design of the cross-coupled and the bi-directional is exploited to recover the system to a functioning yet degraded mode, which is not possible for the simple arrangement.

IV. CONCLUSIONS

This paper has analysed three design arrangements of antagonistic actuation system. All arrangements have been designed to apply Variable Stiffness Actuation by the optimal safe brachistochrone principle. With respect to faults, they all present few critical scenarios for which safety is not guaranteed any more. For this reason a fault management system has been included to survey their functioning, detect fault and adjust the controls to continue the operation in a safe way. The three arrangements with the incorporated safety-related measures are expected to be safe and performing either in fault-free or faulty conditions. The benefits can be quantified in term of performance, by allowing graceful degradation, dependability, by extending the expected lifetime, and safety, by mitigating the consequences of critical failures. Anyway, while safety and performance do not differ significantly, dependability analysis has returned useful information for the comparison of the proposed design solutions. In particular, it has shown how the higher complexity in design of certain arrangements, like as the bi-directional and the cross-coupled arrangements, becomes an asset for the ability of the system to survive to certain critical faults, thus allowing for longer mission time without repair interventions.

REFERENCES

[1] A. Avizienis, J. Laprie, B. Randell and C. Landwehr, *Basic Concepts and Taxonomy of Dependable and Secure Computing*, IEEE Transactions on Dependable and Secure Computing, vol. 1, No. 1, pp. 11-33, January/March 2004.

[2] A. Bicchi and G. Tonietti, *Fast and Soft Arm Tactics: Dealing with the Safety–Performance Tradeoff in Robot Arms Design and Control*, IEEE Robotics and Automation Magazine, Special Issue on ”Safety Among Us”, Vol.11, No.2, June, 2004.

[3] A. Bicchi, E. Colgate, M. Peshkin, *Physical Human-Robot Interaction*, to appear in the ”Handbook of Robotics”, O. Khatib, B. Siciliano (eds.), Springer Verlag, 2006.

[4] A. Hoyland and M. Rausand, *System Reliability Theory: Models and Statistical methods*, 2^{nd} edition, Wiley, New York, 2005.

[5] R. Iserman, Fault-diagnosis systems: an introduction from fault detection to fault tolerance, Springer, Germany 2006.

[6] G. Tonietti and R. Schiavi and A. Bicchi, *Design and Control of a Variable Stiffness Actuator for Safe and Fast Physical Human/Robot Interaction*,In Proc. Int. Conf. on Rob. and Auto., 2005, pp.528-533.

[7] J. Versace *A review of the severity index*, in Proc. of the Fifteenth Stapp Car Crash Conference, no. SAE Paper No. 710881. Society of Automative Engineering, 1971, pp. 771-796.

[8] M. L. Visinsky, J. R Cavallaro and I.D. Walker, *A Dynamic Fault Tolerance Framework for Remote Robots*, IEEE Transaction on Robotics and Automations, Vol. 11, no. 4, August 1995, pp. 477-490.