Safety Intelligent Sensor for Cobot: V2SOM, New device for Rotary Joints

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***Abstract*—This paper deals with the presentation of Variable Stiffness Safety Oriented Mechanism dedicated to rotary joints, as V2SOM. This new device is primarily safety and human friendly oriented. This design ensures the safety of physical Human/Robot Interaction (pHRI). V2SOM presents decoupling capabilities of inertia and torque due to the cohabitation of two functional modes, high and low stiffness modes. Two complementary safety criteria of pHRI are considered in comparison study, the impact force (ImpF) criterion and Head Injury Criterion (HIC) for external and internal damage evaluation of blunt shocks, respectively.**

***Keywords*—V2SOM, compliance, safety, collaborative robot, variable stiffness.**

I. INTRODUCTION

The first sparks of the fourth industrial revolution, in its physical aspect, is taking place with an increasing number of cobots [1][2] assisting the well-experimented humans. This trend requires human friendly cobots with high dynamic performances. In this view, two main approaches are considered for human safety vs robot dynamics tradeoff, speaking of Active Impedance Control and Passive Compliance (PC). The first approach has a low latency of tackling blunt HR collision that reaches up to 200ms [3][4], which may endanger human's safety. In contrast Passive Compliance presents a robust instantaneous response to uncontrolled HR shocks. In general, what makes robots intrinsically dangerous is the combination of high velocities and massive mobile inertia [5]. This latter is a key feature in making cobots behave safely without limiting the desired dynamic performances, i.e. by decoupling the cobot's colliding part inertia from the heavy rotor side inertia via passively compliant joints.

In this respect, the concept of Series Elastic Actuator (SEA) was first introduced in [6], later on enhanced in Series Parallel Elastic Actuator (SPEA) version [7]. By presenting a constant stiffness characteristic, this design cannot cope with cobot's load variation neither with blunt shocks dynamics. To better tackle the variable cobot's dynamics induced by load variation Zinn proposed Macro Mini Actuation [8]. Notice that this approach enhances, essentially, the control aspect. Furthermore, the idea of stiffness coping with wide load variation thus resulted the concept of Variable Stiffness Actuator (VSA) [2]. Till now, several designs have been proposed [2][9] that differs in terms of: stiffness profile, maximum elastic deflection, torque range etc.

The proposed design in this paper is focused on the safety aspect of pHRI. In this view, section 2 introduces the Variable Stiffness Safety Oriented Mechanism (V2SOM) by depicting its working principle as well as its mechanical characteristic. Section 3 presents the problematic of safety criteria, HIC and ImpF, as well as the mechanical model of HR shock [10][11] implemented in Matlab/Simulink platform. Then, a comparison between V2SOM vs a tunable constant stiffness profile is carried out on the basis of the proposed criteria via simulation. The conclusion of the presented work is provided at the end of this present paper.

II. V2SOM AS SAFETY MECHANISM

The VSA's design concept aims to make load-adjustable compliant robots by implementing Variable Stiffness Mechanism (VSM) in series with the actuation system. However, a VSM can simply be described as a tunable spring with a basic nonlinear stiffness profile. In the next, the working principle of V2SOM as well as the design of its first prototype are discussed.

A. *Working principle and architecture of V2SOM*

In general, V2SOM has two working modes between which transition smoothly takes place in case of blunt shock as illustrated in Fig. 1. High stiffness mode (I) defined within deflection range $[0, \theta_1]$ and torque range $[0, T_1]$. T_1 value defines the normal working conditions torque. Exceeding this torque value means that shock absorbing mode is triggered, characterized with low stiffness thus leading to the torque threshold T_{max}.

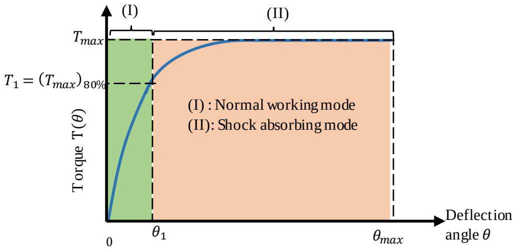

Fig. 1. V2SOM working modes.

From a technical viewpoint, the V2SOM is composed of two blocks each one is intended to a specific functionality. The two blocks are rigidly coupled as shown by a kinematic scheme given in Fig. 3-(a). The V2SOM is attached between link n and link n+1 and coupled to the motor (see Fig. 2).

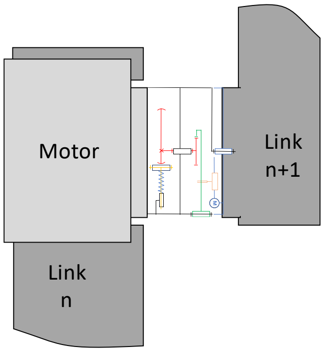

Fig. 2. V2SOM between links.

The upper block, called Stiffness adjusting block, is basically a deflection angle reducer (torque amplifier) with a tunable reduction ratio. This ratio can continuously be adjusted thanks to the actuated joint L_2. The input/output relation between the external torque T_θ and reducer torque T_γ can be written as:

$$\frac{T_\theta}{T_\gamma} = \frac{r_1}{r_2}\left(-1 + \frac{\cos(\alpha)}{\sqrt{\left(\frac{r}{R}\right)^2 - \sin(\alpha)^2}}\right)^{-1} \tag{1}$$

Where r_1 , r_2, R are geometric parameters of the V2SOM defined in the Fig. 3-(b) and r reducer's tuning parameter.

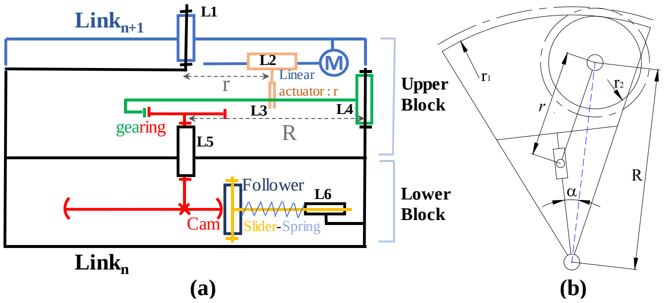

Fig. 3. (a) Kinematic scheme of the V2SOM, (b) Implementation of the stiffness adjustable block with a tunable reducing parameter.

The lower block, called Nonlinear stiffness generator block, is based on a cam/follower mechanism in addition to springs. The cam profile generates the desired torque curve T(γ) vs rotary deflection γ, as defined in Eq. 1. Figure 4-(a) shows the torque curve, where the torque threshold is $T_{max} = 2.05$ Nm, this value leads to the final characteristic shown in Fig. 4-(c). The relation between the deflection angle θ and the input angle α can be written as:

$$\theta = \sin^{-1}\left(\frac{R}{r}\sin\alpha\right) - \alpha \tag{2}$$

With, $\alpha < \operatorname{asin}(\frac{r}{R})$ and $r < R$

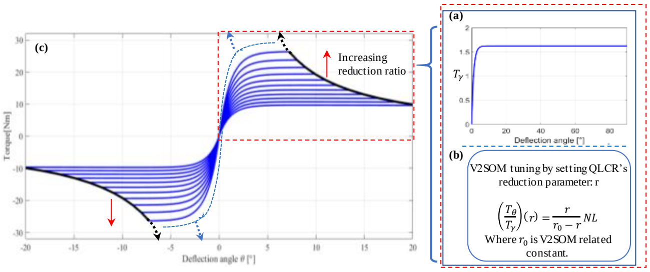

Fig. 4. The whole characteristics of the V2SOM in the two directions of rotation (a) Example of V2SOM basic torque curve with (b) QLCR (C) Illustration of the V2SOM torque characteristic with eleven QLCR settings.

The Figure 4-(c) shows an illustration of the V2SOM characteristic resulting from the Fig. 4-(a) with multiple increasing reduction ratio settings (eleven values of torque tuning). By dint of QLCR the curves in Fig. 4-(a) follows a close formula to (1) with their specific tunable constant r and deflection range. The V2SOM is designed to have a symmetric torque behavior and work in the two directions of rotation. Figure 4 presents the whole characteristics with eleven torque curves for different setup values of $r = \{16.6, 17.6, 18.6, \dots, 25.6, 26.6\}$[mm].

B. *V2SOM Design*

In this section, we present V2SOM's first prototype. The conceptual design in addition to a picture of the actual prototype are highlighted in Figures 5 and 6 respectively.

The revolute joint, $L1$, in Fig. 2 is connecting the two blocks. The reducer's parameter r is tuned using two linear actuators, as shown in Fig. 4-(a). The drive rods are housed in the grooves of the ring gears, defining joint $L3$. Their function is to transmit the torque of the upper bloc to the lower bloc. The rotation of the cam corresponds to the maximum deviation (angle between the lower and upper blocks). The cam presents a symmetric shape along its two principal directions which allows the behavior to be independent from direction of rotation. In addition, the distribution of the applied efforts will be symmetrical. The cam in its rotation movement leads two followers to move along (joint $L6$). Thanks to cam followers the elastic energy of the 8 springs is fully harnessed. The V2SOM's first prototype is shown in Fig. 6.

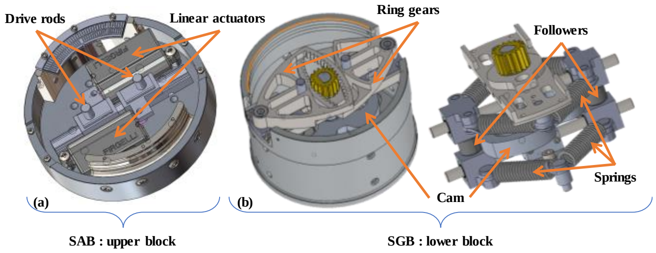

Fig. 5. The CAD model of the upper block (a) and lower block (b) of V2SOM.

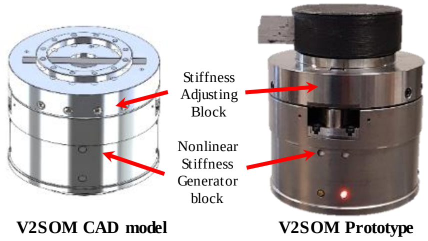

Fig. 6. V2SOM prototype.

All of the important parameters of the new Variable Stiffness Safety Oriented Mechanism have been gathered in the compact form shown in appendix. The overall characteristics from both the mechanical and electrical point of view are reported.

III. SAFETY CRITERIA: V2SOM VS CONSTANT STIFFNESS

The head region is the most critical part of human body compared to the trunk region which is naturally compliant, as indicated by CompC column. The CompC criterion isn't relevant for the head region as the skull is quite rigid. In contrast, HIC and ImpF are considered for their complementary aspect of HR shocks evaluation. HIC is suitable for internal damages evaluation as it quantifies dangerous brain concussions. And ImpF for external damage evaluation. It is important to note that in the context of robot safety , HIC is only relevant to impact to the head with large enough contact area so as not to penetrate or puncture through the skull [12].

A. *Human Robot collision model*

The human head stands as the most critical body region when dealing with the safety problematic of pHRI. Indeed, some previous works [10][11] have investigated this issue. Furthermore, they proceeded with theoretical modeling of this dummy head hardware in crash test.

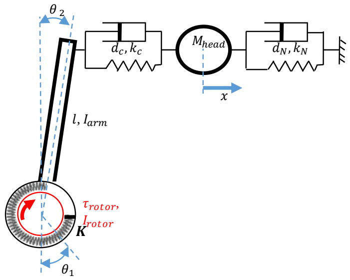

Fig. 7. Mechanical model of dummy head hardware collision against a robot arm

Figure 7 is parameterized according to [11], with:

- Neck viscoelastic parameters $d_N = 12[\text{Ns/m}]$, $k_N = 3300[\text{N/m}]$
- Head's mass $M_{head} = 5.09[\text{Kg}]$ and linear displacement x
- The contact surface viscoelastic parameters $d_c = 10[\text{Ns/m}]$, $k_c = 1500[\text{N/m}]$
- Robot arm contact position $l = 0.6$ [m] and inertia $I_{arm} = 0.14$ [Kgm^2]
- Rotor inertia I_{rotor}, torque τ_{rotor} and angular position θ_1
- VSM's stiffness K and angular deflection $\theta = \theta_1 - \theta_2$

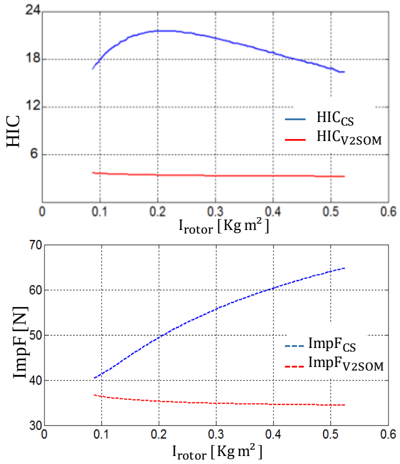

Fig. 8. I_{rotor}simulation results; $(\tau_{rotor}, T_{max}, T_1) = (10,15,12)[\text{Nm}]$; $c = 37[\text{SI}]$; $\dot{\theta}_1 = \pi\ [\text{rads}^{-1}]$.

The collision model allows us to evaluate both ImpF and HIC. The first criterion is directly deduced from simulation data as the applied force on the contact surface. At the opposite, HIC is evaluated by numerically solving the optimization problem [10][11].

B. *Simulation Results of Human Robot collision*

In the following a comparison between V2SOM and a Constant Stiffness (CS) VSM is carried out via simulation of the HR collision model under Matlab/Simulink platform. Herein CS elastic deflection value is set to match V2SOM deflection at 80% of T_{max}. This torque value defines the deflection range of normal operational mode for the V2SOM after which shock absorbing mode is triggered.

The main goal of this simulation is to highlight V2SOM's both inertia and torque decoupling capacity in comparison to an equivalent CS based VSM. The inertia decoupling property is investigated on HIC and ImpF basis.

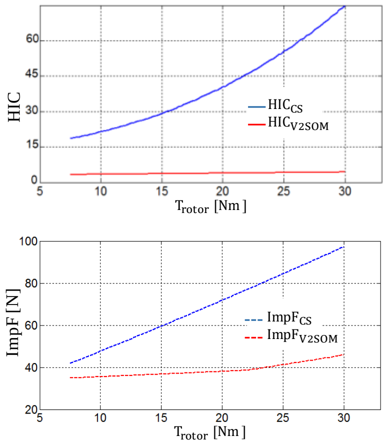

Fig. 9. τ_{rotor} simulation results; $I_{rotor} = 0.175[\text{Kgm}^2]$; $(\tau_{rotor}, T_{max}, T_1) = (7.5 \rightarrow 30, 15,12)$ [Nm]; $c = 37$; $\dot{\theta}_1 = \pi[\text{rads}^{-1}]$

***Inertia decoupling*:** Figure 8 shows that V2SOM presents more than 80% gains on HIC basis compared to CS. On the other hand, a gain of 10% up to 40% is noticed on ImpF curves.

HIC_{V2SOM} and $ImpF_{V2SOM}$ are quite steady for a large range of rotor inertia. This property leads to conclude that V2SOM presents a high inertia decoupling capability compared to a CS based VSM. Ideally, this characteristic means the human body, in case of HR shock, is subject to only arm side inertia rather than the heavy resulting arm and rotor inertia.

As previously shown by Haddadin in [5], lower values of the mobile mass allows higher velocities to maintain the same safety level. By considering V2SOM inertia decoupling capacity in addition to Haddadin's results, the proposed design allows better dynamic performances for the cobot without overreaching the safety thresholds.

***Torque decoupling*:** Quasi constant behavior is noticed for V2SOM in Fig. 9, where large variation of motor applied torque τ_{rotor} does slightly affect HIC and ImpF values in comparison with CS based VSM.

It should be mentioned that the moderate gain, of 10% until 40%, on ImpF basis can be enhanced with a well-designed contact surface of the robot arm. On the contrary, brain concussion quantified with HIC is well tackled by adopting a V2SOM like elastic behavior.

IV. CONCLUSION & FUTURE WORK

In this paper, we present a new variable elastic behavior in view of designing a rotary VSM which is primarily safety and human friendly oriented, resulting in V2SOM. This latter is proposed to:

- Cope with the problems of existing models in normal operational routines, for instance passively limiting elastic deflection caused by gravity or reducing the risk of explosive motion.
- Ensure better dynamic performances without compromising the safety threshold, thanks to its inertia and torque decoupling capabilities.

In addition to the safety and control related advantages of this design, the prototype is online tunable with no need of energy to maintain a certain safety threshold.

Currently, simpler and more lightweight variable stiffness safety oriented mechanism is under development. So that, future works will focus on the implementation and the experimental evaluation of the use of several V2SOMs simultaneously in a robotic arm.

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APPENDIX

Mechanical				
1	Lowest Safety Threshold Torque		[Nm]	9.7
2	Safety Threshold Variation Time (from nominal level towards completely Stiff state)	With/without load. (prone improvement)	[s]	1.6
3	Maximum Stiffness		[Nm/rad]	∞
4	Minimum Stiffness		[Nm/rad]	~ 0
5	Maximum Elastic Energy		[J]	2.98
6	Maximum deflection	with max. Safety Threshold	[°]	0
		with min. Safety Threshold	[°]	20
7	Active Rotation Angle		[°]	±∞
8	Angular Resolution		[°]	0.0313
9	Weight		[Kg]	0.970
Electrical				
10	Nominal Voltage		[V]	12
11	Nominal Current		[A]	0.010
12	Maximum Current		[A]	0.500
Control				
13	Voltage Supply		[V]	12
14	Nominal Current		[A]	0.105
15	I/O protocol		CAN [1 Mbit/s]	

V2SOM parameters [13]. The V2SOM Variable Stiffness Safety Oriented Mechanism was developped within the SISCob project supporeted by National Research Agency.