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Mechanically stiffness-adjustable actuator using a leaf spring for safe physical human-robot interaction

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1. Introduction

The development of robots that can work alongside humans in our homes and workspaces to assist human daily activities has been ongoing for a long time. Up to now, most robotic systems, consisting of rigid components, are powerful, fast, heavy, and strong. Most are without any capacity for interaction with humans under safe constraints. To work, cooperate, assist, and interact with humans, the new generation of robots must have an anthropoid structure that accommodates interactions with humans and adequately fits in an unstructured and sizable environment.

Therefore, several categories of safety policies have been discussed for safety between humans and robot. A definition of human-robot interaction (HRI) awareness based on research from computer-supported cooperative work (CSCW) was specified. The domain of human-robot interaction can be divided into two main groups: one is cognitive human-robot interaction (cHRI) concerning communication between humans and robots through the many channels available to humans (vision, images, sounds, spoken language, or facial expression, etc.); the other is physical human-robot interaction (pHRI) concerning that robots are distinct from computers in that robots physically embody the link between perception and actions [1, 2]. In addition, pHRI can also be subdivided into two parts. First, if a collision is detected by a direct contact sensor, the robot will stop itself or accrue a corresponding motion to minimize the collision force between the human and the robot system. Second, for a relatively large collision, the collision force or shock can be absorbed directly by passive components. For safe human-robot interactions, safe robot systems can be achieved with either active or passive component systems. cHRI and the first part of pHRI are grouped in the active component systems, and the second part of pHRI falls into the passive component system.

In active component systems, robot system controllers are used to create an antagonistic response to orient the robots to dynamic collisions, and robot systems suffer from low bandwidth unless they are fitted with an expensive precision instrument. In addition, accurate dynamic parameters for the robot systems are required for safe human-robot interaction, and sensor noise and the actuator's performance also must be considered. Recently, to efficiently achieve intrinsically safe robot actuation, several techniques and approaches for passive component systems have been devised. The safety device based on passive components usually consists of springs or flexible material. The Series Elastic Actuator (SEA) uses low impedance or high compliant and/or viscous elements in series between transmission mechanisms and loads [3-10]. However, a soft spring used on robot systems can absorb the collision force but causes positioning inaccuracy. In contrast, a stiff spring brings good performance with precision and high speed but has a higher probability of injury upon collision with a human.

To cope with this problem, the safe joint mechanism (SJM) and safe link mechanism (SLM) combing passive mechanisms with slider structures, linear springs, and transmission shafts to achieve nonlinear characteristics to vary mechanical stiffness as proposed [11-14]. However, the stiffness of the SJM or SLM is variable passively. Therefore, under safe conditions, it could not cover all situations, such as achieving good performance with precision and high speed. Thus, under safe conditions, how a robot achieves good performance with precision and high speed is an important issue. To represent human safety associated with a dynamic collision, the Head Injury Criterion (*HIC*) [15], which quantitatively measures head injury risks in car crash situations, was used to evaluate the tolerant level of human-robot impact [16, 17]. A manipulator's acceptable velocity regarded as an important performance index can be improved in several ways, for example, limiting the velocity commands of the robot, reducing the stiffness of the robot's cover using soft material, and reducing the transmission stiffness between the actuator and the output link via passive compliance. To obtain the ideal stiffness to satisfy the tolerant level of human-robot impact, active variable stiffness actuators using a variable stiffness transmission mechanism to actively vary the mechanical stiffness of the given system as proposed.

Active variable stiffness actuators can be grouped into two categories. The first group is antagonistic actuation: two actuators connecting the same block (joint) through nonlinear mechanical springs working in an antagonistic configuration were designed and allowed the mechanical impedance of the actuator to be changed during motion [18, 19]. Another group is serial actuation; most implementations used two actuators to control the position and stiffness of the joint [20-23]. Although these active variable stiffness actuators are advantageous for dexterous manipulation and their compliant component is good for collision safety, the control theory for two antagonistic motors moving synchronously is complex and the size of actuation is huge.

In this research, a new active variable stiffness mechanism, the Active Variable Stiffness Elastic Actuator

(AVSEA), is proposed. The AVSEA not only possesses the same characteristics as the active variable stiffness mechanism to implement the above requirements (safety and performance) but also makes controlling it easier (a simple PID position control is used to independently control the position and stiffness of the AVSEA).

This paper is organized as follows. Section 2 presents the main ideas of precise position movement actuation and the active variable stiffness actuator (safe actuation). In section 3, the design of the AVSEA is explained. Section 4 presents experimental results to show that the AVSEA is capable of providing precise position movements and safe human-robot interaction. Finally, conclusions are made in Section 5.

2. Precise position movement actuation/safe actuation

Precise position movement actuation and safe actuation are presented in this section. The main concept of precise position movement actuation is the use of a new ball screw drive system for greater efficiency and accurate reservations. For safe actuation, an active variable stiffness serial configuration (adaptable compliance) is discussed.

2.1. New motor-ball screw drive system

To keep the ability of the actuator to make precise position movements and trajectory tracking control easier, as in classic robotic systems, a motor-ball screw drive system was designed, as shown in Fig. 1. A cable is fixed on the moving plant and connected with the output link; when the DC-motor01 drives the ball screw, the output link is rotated because of the cable connected to the moving plant.

The output link angular displacement of the system θ_{out} is given by

$$\theta_{out} = \theta_m G \tag{1}$$

where θ_m is the angular displacement of the DC-motor01, and G is the gear reduction ratio of the system.

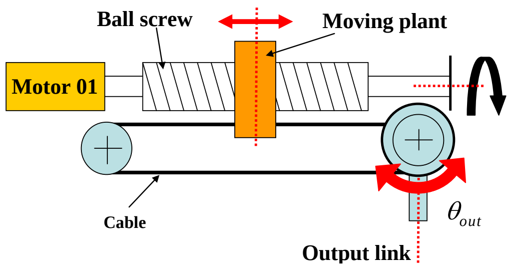


Fig. 1 Motor-ball screw drive system

To shorten the length of the ball screw to reduce the size of the system, a block assembly with a propelling sheave and a fixed pulley is used, as shown in Fig. 2. In the block assembly, $X_P{}'$ is the position of the propelling sheave, and X_P is the position of the propelling sheave before the external force is generated. $X_E{}'$ is the position of the end point of the cable, and X_E is the position of the end point of the cable before the external force is generated. The movement distance between the propelling sheave and the end point of the cable is given by

$$-2\left(X_P{}' - X_P\right) = X_E{}' - X_E \tag{2}$$

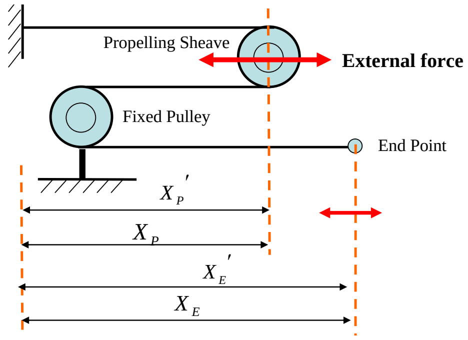


Fig. 2 A block assembly (with propelling shave and fixed pulley)

By combining the system and block assemblies, the new motor-ball screw drive system (with block assemblies) is presented in this paper. As shown in Fig. 3, the propelling sheave of the block assembly is fixed on the moving plant, and the ends of cable fasten to the output link. When the ball screw is driven and rotated by the DC-motor01, the moving plant fixed on the ball screw will advance or draw back in its own axial direction, and the propelling sheave fixed on the moving plant will advance or draw back, too. Finally, the output link of the new system (with the block assembly) is rotated because of the endpoint of the cable is fixed on the output link. The angular displacement of the output link in the new system with block assembly $\theta_{out}{}'$ is given by

$$\theta_{out}{}' = 2\theta_{out} \tag{3}$$

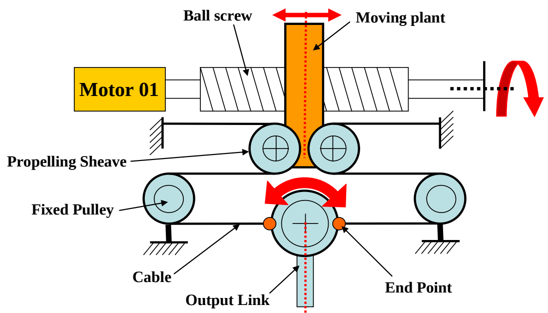


Fig. 3 New motor-ball screw drive system (with block assembly)

2.2. Active variable stiffness serial configuration

The design of an active variable stiffness serial configuration can be expressed by the series combination. To explain the properties of the configuration, a simple beam system is used, as shown in Fig. 4. P is the concentrated load, L is the length of the beam, E is the modulus of elasticity (Young's modulus), and I is the moment of inertia. The deflection at the end point of the beam δ_B is given by [24]

$$\delta_B = \frac{PL^3}{3EI} \tag{4}$$

From Eq. (4), the deflection at end point of the beam δ_B is changed by the length of the beam L.

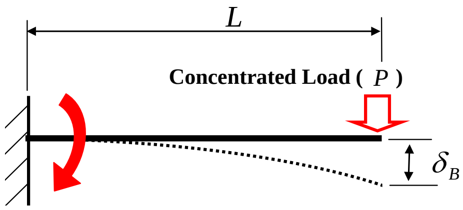


Fig. 4 A beam system

In this paper, a leaf spring is used instead of the beam, and to obtain the ability to control the deflection at the end point of leaf spring, an active variable stiffness serial configuration is designed, as shown in Fig. 5. In this configuration, a screw is rotated by the DC-motor02, and the moving plant advances or draws back in its own axial direction. By changing the position of the moving plant, the active variable stiffness serial configuration has the ability to obtain an effective length for the leaf spring l, and a change in the effective length of the leaf spring results in changing stiffness.

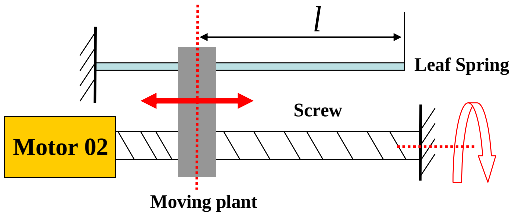


Fig. 5 Schematic of the active variable stiffness serial configuration

2.3. Active variable stiffness elastic actuator (AVSEA)

The new motor-ball screw drive system makes precise position movements, and the active variable stiffness serial configuration has the ability to minimize large impact forces due to shocks, thereby safely interacting with the user. In this paper, the main idea of the AVSEA designed and applied for safe physical human-robot interaction is to combine these two important properties.

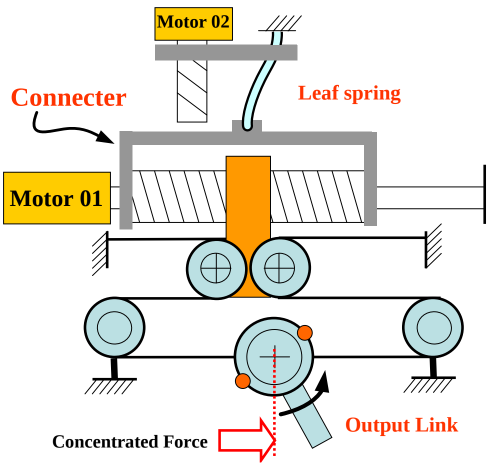


Fig. 6 The function of the active variable stiffness elastic actuator (AVSEA) to minimize impact forces

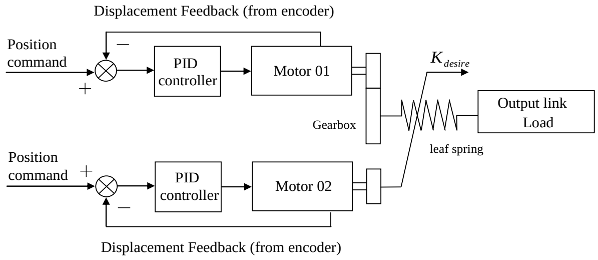


Fig. 7 AVSEA control topology

As shown in Fig. 6, there is a connecter between the new motor-ball screw drive system and the serial configuration; the connecter connects these two configurations, the AVSEA was built. By the new motor-ball screw drive system (with the block assembly), the output link of AVSEA makes precise angular position movements. When the impact forces (concentrated force) active on the output link of AVSEA, the force will be transfer to the leaf spring, the AVSEA has the ability to minimize large impact forces due to shocks, to safely interact with the user. The detail structure of the AVSEA will be described in the next section. Fig. 7 depicts the control topology for the AVSEA. The AVSEA consists of two DC motors: one is used to control the position of the joint, and the other is used to control the effective length of the leaf spring to adjust the stiffness of the AVSEA. In the AVSEA, each motor is independently controlled by a simple PID controller. The motor has displacement feedback from an encoder that forms a position-closed loop for controlling the motor.

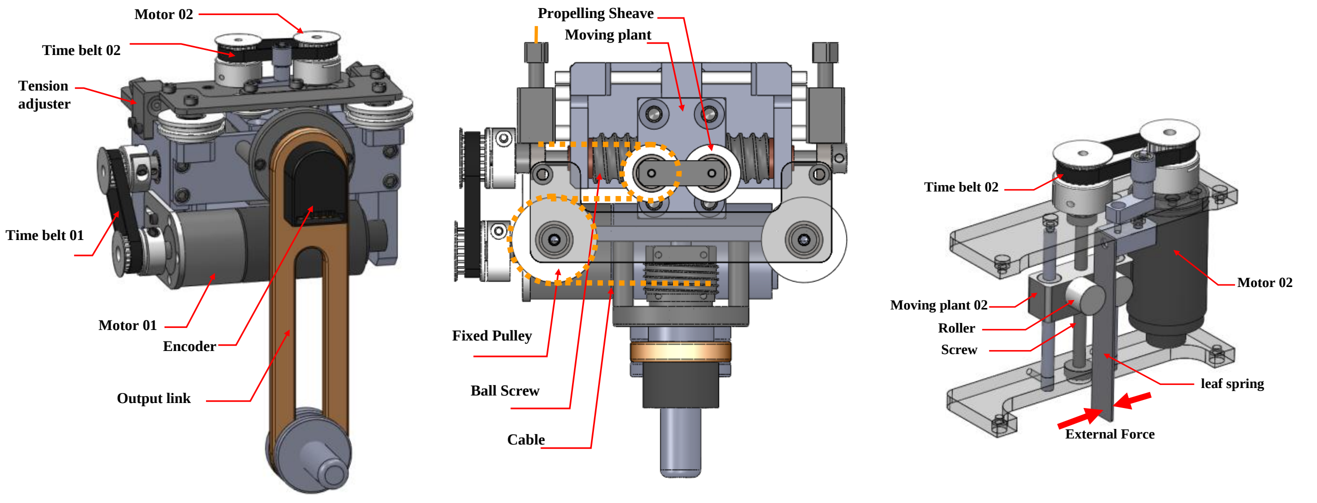
3. Design of an active variable stiffness elastic actuator (AVSEA)

The two main mechanisms, the system and the serial configuration, are designed to obtain the two desired characteristics of the AVSEA, namely, accurate movement and safe human-robot interaction. The 3D AVSEA model is shown in Fig. 8, a.

In the new system, a ball screw is driven and rotated by the DC-motor01, and a moving plant is placed on the ball screw. When the ball screw is rotated by the DC-motor01, the moving plant advances or draws back in its own axial direction. A cable is connected to the propelling sheave, fixed pulley, and output link; when the moving plant moves, the output link rotates. According to the abovementioned moving structure, the AVSEA has the ability to move accurately. The 3D model of the AVSEA new motor-ball screw drive system is shown in Fig. 8, b.

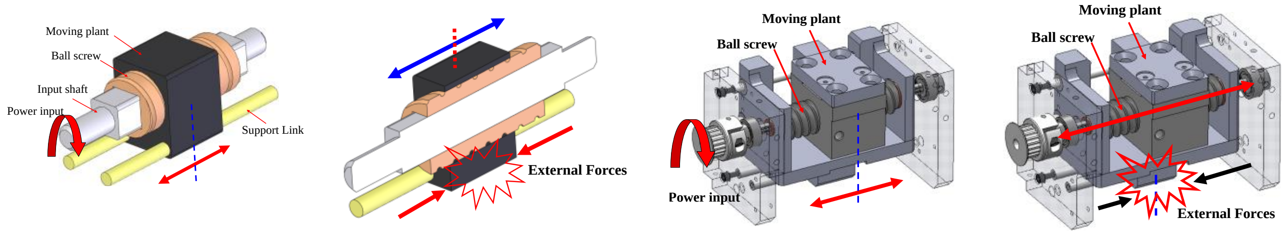
In the active variable stiffness serial configuration, a screw is rotated by the DC-motor02, and the moving plant02 is placed on the screw. When the screw is rotated by the DC-motor02, the moving plant advances or draws back in its own axial direction. Two rollers are fixed on the moving plant02; these rollers will define the effective length of the leaf spring. According to the abovementioned moving structure, the AVSEA's active variable stiffness serial configuration has the ability to obtain stiffness as soft as possible to minimize large impact forces due to shocks, to safely interact with the user, and/or to become as stiff as possible to make precise position movements or trajectory tracking control easier. The 3D model of the active variable stiffness serial configuration is shown in

Fig. 8, c. The key feature of the AVSEA mechanical structure is the relation between the input shaft and the ball screw of the new motor-ball screw drive system. The actuation principle of this system is illustrated in Fig. 9. Fig. 9, a shows the working concept. An input shaft passes through the center of the ball screw. When the input shaft is driven and rotated by a motor, the ball screw will be driven and rotated. Then the moving plant, which is fixed on the ball screw, advances or draws back in its own axial direction. Fig. 9, b is the cross-section diagram. In addition,



a b c

Fig. 8 3D AVSEA model



a b c d

Fig. 9 3D model of the AVSEA new motor-ball screw drive system: a – the concept of the AVSEA new motor-ball screw drive system, b – the cross-section diagram of the AVSEA new motor-ball screw drive system, c – the detail structure of the AVSEA new motor-ball screw drive system, d – the AVSEA new motor-ball screw drive system with external forces

when external forces, impacts, or shocks are exerted on the moving plant, the external forces will push/pull the moving plant. Because the input shaft goes through the center of the ball screw, the ball screw with the moving plant will slide in the same axial direction as the input shaft.

Based on the concept of this system, the detailed structure of the AVSEA new motor-ball screw drive system is shown in Fig. 9, c. When external forces, impacts, or shocks are exerted on the output link, the external forces will push/pull the moving plant through a cable, and then all of the structure, including the ball screw and the moving plant, will be moved and slide in the same axial direction as the input shaft, as shown in Fig. 9, d. With this unique mechanical structure, the AVSEA can minimize large impact forces due to shock and safely interact with the user.

4. System experiment evaluation

In this section, experiments were conducted to evaluate the properties and abilities of the AVSEA. Fig. 10 is the picture of the AVSEA consisting of two DC motors, one ball screw, and a leaf spring. The rotation of the axis is measured by an encoder fixed on the output link. The dimensions of the AVSEA, design parameters, and some detailed specification are listed in Table.

Table

AVSEA specifications

Parameters	Value
Weight (include two motors)	2.2 kg
Length x Width x Height	120 x 110 x 90 mm
DC-motor	2
Max. Output Torque	29 Nm
Max. Output Speed	60 rpm
Max. Stiffness	Equivalent to rigid joint stiffness
Min. Stiffness	0.085 Nm/deg
Motion Space	±150°
Leaf spring (thickness x width)	3 x 10 mm
Max. Output Link Deflection	±40°

4.1. Adaptive compliant property

An experiment was designed to interpret the adaptive compliant property of the AVSEA. The experiment comprises four stages. First, by using a simple PID controller, the output link of the AVSEA was rotated and kept in a vertical direction. Second, the output link of AVSEA was manually deflected in a counterclockwise direction away from the 0° (equilibrium point) with the situation whereby the motor was still working. Third, the output link was deflected in a clockwise direction. Fourth, the link was released. As shown in Fig. 11, the result is a plot of the angle with time, and the photograph shows the beginning and ending positions of the AVSEA. The experiment shows that an adaptive compliant configuration was used to make the interaction between robots and humans safer and more natural and that the AVSEA has the ability to interact with people or unknown environments under safety constraints with an adaptive compliance configuration.

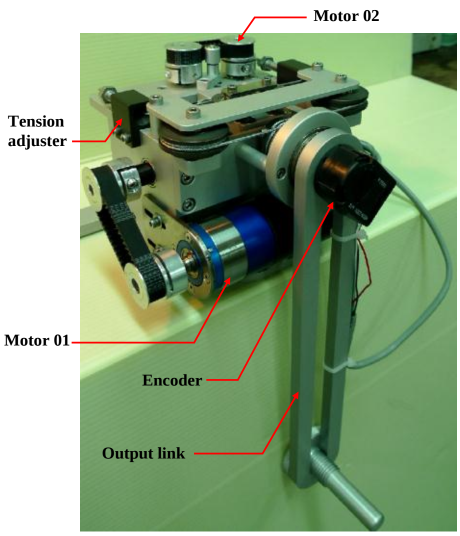


Fig. 10 The active variable stiffness elastic actuator

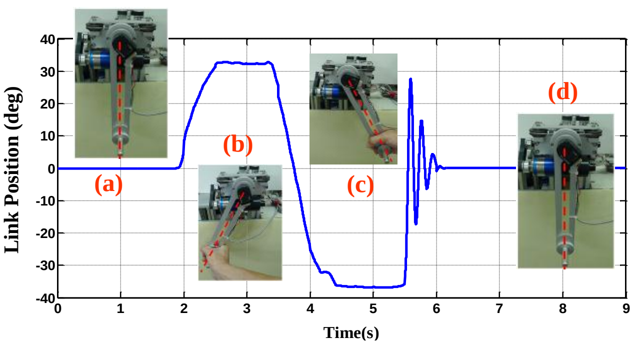


Fig. 11 Adaptive compliant property for the active variable stiffness elastic actuator

4.2. Active variable stiffness property

By changing the effective length of the leaf spring, the AVSEA is able to vary the stiffness. In this experiment, a force sensor is used to measure the external force at the end point of the output link, and an encoder is used to measure the angular deflection of the output link. As it is shown in Fig. 12, L is the effective length of the leaf spring. The stiffness of the AVSEA is changed with the effective length of the leaf spring.

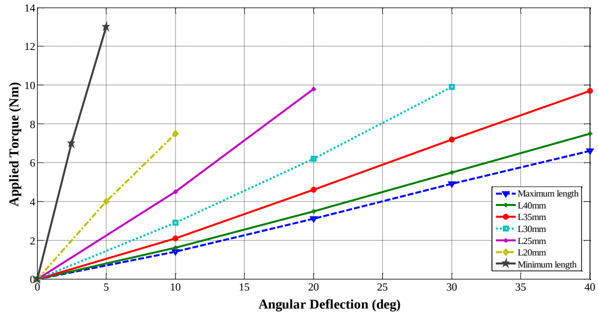


Fig. 12 Measure stiffness of the AVSEA

4.3. Response to position command with variable stiffness

The step response of the designed AVSEA system with different leaf spring (maximum and minimum) lengths is given in Fig. 13. The position of the AVSEA changes from 0° to 30° by using a simple PID controller; the result is a plot of the angle with time. As it is shown in Fig. 13, when the length of the AVSEA leaf spring is the maximum (the stiffness is the minimum), vibration due to the position command over 0.82 sec and the actuator is at 5.5° angle offset because of the gravity, the precise position movement ability is worse. If the length of the leaf spring of the AVSEA is the minimum (the stiffness is the maximum), vibration does not occur, the AVSEA has good precise position movements, and the maximum error of final angular position value is less than 0.2°. The experiment shows that the AVSEA has the ability to obtain different stiffnesses by changing the length of the leaf spring of the AVSEA, and the AVSEA with maximum stiffness shows a better response than the AVSEA with the minimum.

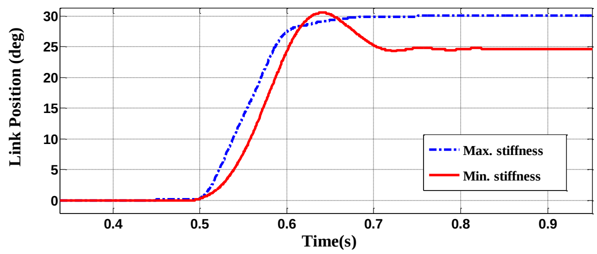


Fig. 13 Response to position command with variable stiffness

4.4. Safety robot system

● *HIC*

For a typical robot, the margin available for designing to satisfy safety and performance requirements is the intersection of the ranges of the tip-velocity and payload values of acceptable designs. Since the tip-velocity and payload values determine how to design a safe robot, several safety criteria based on these two factors have been developed. For example, to represent human safety associated with a dynamic collision, the *HIC* [15], which quantitatively measures head injury risks in car crash situations, was used to evaluate the tolerant level of human-robot impact in many studies [11, 16, 17]. A *HIC* value equal to or greater than 1000 is typically associated with an extremely severe head injury. A value less than 100 is considered suitable for normal operation of a machine physically interacting with humans. The *HIC* for compliant manipulators [17] can be given as follows

$$HIC = 2\left(\frac{2}{\pi}\right)^{\frac{3}{2}}\left(\frac{K_{cov}}{M_{oper}}\right)^{\frac{3}{4}}\left(\frac{M_{rob}}{M_{rob}+M_{oper}}\right)^{\frac{7}{4}} V_{max}^{\frac{5}{2}} \tag{5}$$

where M_{oper} is the impacted operator mass, K_{cov} is the lumped stiffness of a compliant cover on the arm, and V_{max} is the maximum velocity of the end-effector. The compound inertia M_{rob} is defined as

$$M_{rob}\left(K_{transm}\right) = M_{link} + \frac{K_{transm}}{K_{transm}+\gamma} M_{rotor} \tag{6}$$

where γ is the rigid joint stiffness. Note that low transmission stiffness K_{transm}, which decouples the rotor mass M_{rotor} from the link mass M_{link}, dominates the major effect of the M_{rob}. Moreover, the acceptable velocity under the safety constraint can be written as

$$V_{max} = \left[\frac{HIC_{max}}{2\left(\frac{2}{\pi}\right)^{\frac{3}{2}}\left(\frac{K_{cov}}{M_{oper}}\right)^{\frac{3}{4}}\left(\frac{M_{rob}\left(k_{transm}\right)}{M_{rob}\left(K_{transm}\right)+M_{oper}}\right)^{\frac{7}{4}}}\right]^{\frac{2}{5}} \tag{7}$$

where the maximum tolerant max *HIC* can be chosen less than 100, a suitable value for normal operation of a machine physically interacting with humans. As shown in Fig. 14, we can see that when V_{max} = 1 m/s, the *HIC* of the AVSEA is much better than the SEA [16].

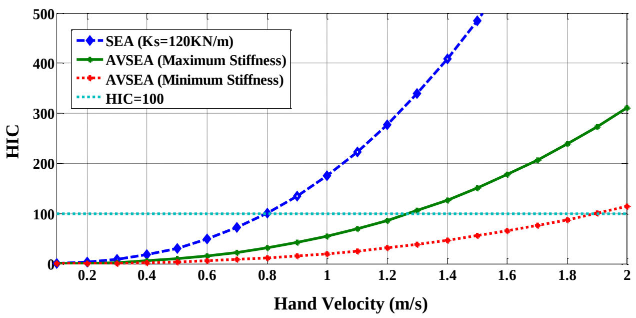


Fig. 14 The head injury criterion (*HIC*) for SEA and AVSEA

An *HIC* of 100 is a suitable value to normal operation of a machine physically interacting with humans. The model parameters for AVSEA are: maximum K_{transm} = 3000 kN/m (equivalent to rigid joint stiffness), minimum $K_{transm} = 0.95$ kN/m, $\gamma = 3000$ kN/m, $K_{cov} = 25$ kN/m, $M_{oper} = 4$ kg, $M_{rotor} = 0.7$ kg, $M_{link} = 0.5$ kg.

5. Conclusions

In this paper, an active variable stiffness elastic actuator design and application for safe physical human-robot interaction are presented. By changing the effective length of the leaf spring, the AVSEA has the ability to minimize large impact forces due to shocks, to safely interact with the user, and/or become as stiff as possible to make precise position movements or trajectory tracking control easier. From the analysis and experiments of this research, the following conclusions are drawn:

1. The AVSEA has the ability to interact with people or unknown environments under safety constraints due to the passive components configuration.
2. The AVSEA, which has a passive components configuration, shows a faster response than systems with an active component.
3. The stiffness of the AVSEA is adjustable. The AVSEA can achieve very high stiffness, like a rigid system, to make precise position movements.
4. For dynamic collision, the AVSEA is able to minimize large impact forces to provide better safety in case of an existing unexpected impact.

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PLOKŠČIOSIOS SPYRUOKLĖS MECHANINIU STANDUMU REGULIUOJAMA PAVARA SAUGIAI FIZINEI ŽMOGAUS IR ROBOTO SĄVEIKAI UŽTIKRINTI

R e z i u m ė

Straipsnyje aprašoma aktyvi kintamo standumo tamprioji pavara, suprojektuota ir pritaikyta saugiai fizinei žmogaus ir roboto sąveikai užtikrinti. Ši pavara susideda iš dviejų nuolatinės srovės variklių: vienas iš jų naudojamas jungčių pozicijos kontrolei, o kitas sistemos standumui reguliuoti. Keičiant plokščiosios spyruoklės efektyvųjį ilgį, ši pavara gali iki minimumo sumažinti smūgio jėgas priklausomai nuo jų kitimo, saugiai sąveikauti su vartotoju ir/arba padidinti standumą ir judesio pozicionavimo tikslumą arba palengvinti sekti judesio trajektoriją. Bandymų rezultatai rodo, kad aktyvi kintamo standumo tamprioji pavara gali tiksliai pozicionuoti ir užtikrinti saugią žmogaus ir roboto sąveiką.

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MECHANICALLY STIFFNESS -ADJUSTABLE ACTUATOR USING A LEAF SPRING FOR SAFE PHYSICAL HUMAN-ROBOT INTERACTION

S u m m a r y

An Active Variable Stiffness Elastic Actuator (AVSEA), which is designed and applied for safe physical human-robot interaction, is presented in this paper. The AVSEA consists of two DC motors: one is used to control the position of the joint, and the other is used to adjust the stiffness of the system. By changing the effective length of the leaf spring, the AVSEA has the ability to minimize large impact forces due to shocks, to safely interact with the user, and/or to become as stiff as possible to make precise position movements or trajectory tracking control easier. Experiment results are presented to show that the AVSEA is capable of providing precise position movements while offering safe human-robot interaction.

Keywords: mechanically stiffness, adjustable actuator, leaf spring, physical human-robot interaction.

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