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An Active-Passive Variable Stiffness Elastic Actuator for Safety Robot Systems

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Abstract— **For classical robotic applications, robotic systems consist of servo motors, high-ratio reduction and rigid links; mechanical designers prefer to designing robotic applications as stiff as possible to make robots manipulate with remarkable speed and precise position movements. However, these robotic applications can hardly interact with people and environments under safety constraints. It poses the very fundamental problem of ensuring safety to humans and protecting the robot. This paper presents an active-passive variable stiffness elastic actuator (APVSEA) which is designed for safety robot systems. The APVSEA 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. The stiffness is generated by two antagonistically nonlinear springs. By changing the preload length of the two antagonistically nonlinear springs, APVSEA 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. Experiment results are presented to show that APVSEA is capable of providing precise position movements while offering safe human-robot interaction.**

I. Introduction

The development of robots that can work alongside humans in our homes and workspaces to assist human daily activities though physical interaction, informational interaction, etc., has been ongoing for a long time. That is the reason why the research on physical human-robot interaction that considers the trade-off between safety and performance has emerged in the field of modern robotics [1].

Traditionally, industrial robots are heavy, fast, strong and powerful. Most of them are without any capacity of interaction with humans under safety constraints. Therefore, under the safe condition, how a robot achieves good performances in precision and high-speed is becoming one of the most important issues. 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, lowering the stiffness of the robot's cover using soft material, reducing the transmission stiffness between the actuator and the output link via passive compliance [2][3]. Recently, in order to efficiently keep robots with intrinsically safe robot actuation, several techniques and approaches have been devised. SEA, these actuators use low impedance or high compliant and/or viscous elements in series between transmission mechanisms and loads, and moreover, both linear and rotary SEA designs have been presented in [4-6]. The safe joint mechanism(SJM) and the safe link mechanism(SLM) which passive mechanisms proposed in are combined with slider structures, linear springs and transmission shafts, The mechanisms perform nonlinear characteristics by using the idea of the transmission angle of the four-bar linkage and the characteristics of the slider mechanism in combination with the springs [7-10]. Variable stiffness actuator uses a variable stiffness transmission mechanism to vary mechanical stiffness of the given system [11]. One actuator with two non-linear mechanical springs working in antagonistic configuration was designed. It allows changing the mechanical impedance of the actuator during motion [12]. In [13-15] most of the proposed implementations make use of two actuators to control the position and stiffness of the joint. By changing the link position or the effective length of the spring results in change in stiffness. In [16]a robot arm with actuator systems using a pneumatic artificial muscle is developed. Most of the proposed implementations of this kind of actuators make use of two non-linear mechanical pneumatic artificial muscles in antagonistic configuration. The pneumatic artificial muscle is light weight and flexible.

An active-passive variable stiffness elastic actuator (APVSEA), designed for safety robot systems is presented in this paper. It discusses in detail the APVSEA mechanism, the stiffness adjuster and comparative performances between an actuator with maximum and minimum stiffness. This paper is structured as follows: section II presents the main ideas of precise position movement actuation and active-passive variable stiffness actuator (safe actuation). In section III, the design of an active-passive variable stiffness elastic actuator (APVSEA) is explained. The APVSEA consists of two DC-motors, one ball screw, one screw and four variable stiffness springs. The rotation of the axis is measured by an encoder which is fixed on the output link. Section IV presents experiment results to show that APVSEA is capable of providing precise position movements and safer human-robot interaction. Finally, the conclusions are made in Section V.

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II. Precise Position Movement Actuation / Safe Actuation

The precise position movement actuation and safe actuation are presented in this section. The main concept of the precise position movement actuation is the use of a ball-screw and time belt for greater efficiency and making accurate reservations. For the safe actuation, active and passive variable stiffness serial configurations (adaptable compliance) are discussed.

A. 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. Note that a ball-screw is driven and rotated by a DC-motor01; because the ball screw is rotated, the moving plant which is fixed on the ball screw will advance or draw back in its own axial direction. There is a time belt fixed on the moving plant and connected with the output link; when the DC-motor01 drives the ball screw, the moving plant is moved. Finally, the output link is rotated and moves because of the time belt which is connected to the moving plant.

B. Passive Variable Stiffness Serial Configuration

The design of a passive variable stiffness serial configuration can be expressed by the series combination. In order to explain the properties of the passive variable stiffness serial configuration, a simple spring system with a linear spring is used, as shown in Fig 2. x is the position of the moving plant (block), and x_p is the position where no forces are generated. The forces on the block are given by:

$$F = k \cdot (x_p - x), \quad \text{if } x \le x_p \tag{1}$$

Differentiating (1) with respect to the position x, the stiffness is expressed as:

$$K = \frac{dF}{dx} = -k \tag{2}$$

This result shows that the stiffness of the compliance is uncontrollable.

When the springs with a quadratic characteristic are used, the force is expressed as:

$$\begin{aligned} F &= k \cdot (x_p - x)^2 \\ &= k \cdot x_p{}^2 - 2k \cdot x_p \cdot x + k \cdot x^2 \end{aligned} \tag{3}$$

The stiffness of the nonlinear spring compliance system is obtained

$$K = \frac{dF}{dx} = 2kx - 2k \cdot x_p \tag{4}$$

Where the stiffness varies as a linear function of the block position x.

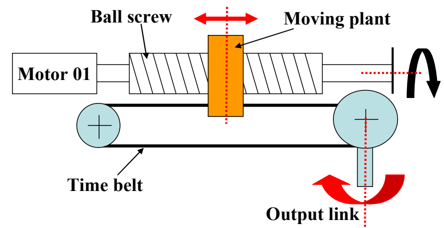

Fig. 1. Motor-Ball screw Drive System.

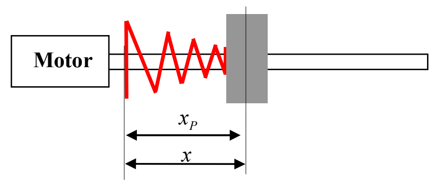

Fig. 2. Passive variable stiffness serial configuration.

C. Active Variable Stiffness Serial Configuration

From (4), the stiffness of the nonlinear spring compliance system is dependent on the position of the block. In order to obtain the ability to control the stiffness of the spring compliance system so as not to depend on the position of the block, a new structure model, active variable stiffness serial configuration, was built. To explain the properties of the active variable stiffness serial configuration, a simple linear antagonistic setup with two linear springs having the same spring constant is used, as shown in Fig 3. x is the position of the moving plant (block), x_p is the position where no forces are generated, and x_{oA} and x_{oB} are the controllable position (preload distance of the spring). The forces on the block equal the sum of the forces of both springs:

$$\begin{aligned} F &= k(x_{oA} + (x_p - x)) - k(x_{oB} + (x - x_p)) \\ &= -2kx + k(x_{oA} - x_{oB}) + 2kx_p \end{aligned} \tag{5}$$

Differentiating (5) with respect to the position x, the stiffness becomes

$$k = \frac{dF}{dx} = -2k \tag{6}$$

This result shows that the stiffness of the compliance is uncontrollable.

When the springs with a quadratic characteristic are used, the force is expressed as:

$$F = k(x_{oA} + (x_p - x))^2 - k(x_{oB} + (x - x_p))^2$$
$$= -2kx(x_{oA} + x_{oB}) + k(x_{oA}{}^2 - x_{oB}{}^2) + 2k(x_{oA} \cdot x_p + x_{oB} \cdot x_p) \quad (7)$$

The stiffness of the nonlinear spring compliance system, active variable stiffness serial configuration, is obtained:

$$K = \frac{dF}{dx} = -2k(x_{oA} + x_{oB}) \quad (8)$$

Fig. 4 shows the relation between the block movement and the force on the block ($k = 1$, $x_p = 6$), where the control parameters x_{oA} and x_{oB} are ($x_{oA} = 1,2,3$ and $x_{oB} = 1,2,3$). Note that the stiffness of the active variable stiffness serial configuration is controllable.

D. *Active-Passive Variable Stiffness Elastic Actuator (APVSEA)*

A motor-ball screw drive system has the property of making precise position movements and the active-passive variable stiffness serial configurations 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 active-passive variable stiffness elastic actuator designed for safety robot systems is to combine these two important properties. As shown in Fig. 5, there is a connecter between the motor–ball screw precise drive system and the active-passive variable stiffness serial configuration; the connecter connects these two configurations, and as a result, an active-passive variable stiffness elastic actuator was build. The actuator has the ability to minimize large impact forces due to shocks, thereby safely interacting with the user and/or becoming as stiff as possible to make precise position movements or trajectory tracking control easier.

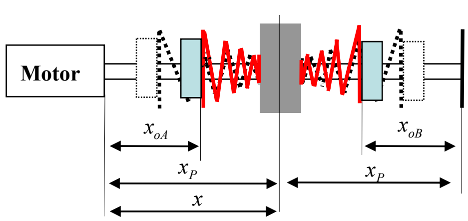

Fig. 3. Active Variable Stiffness Serial Configuration.

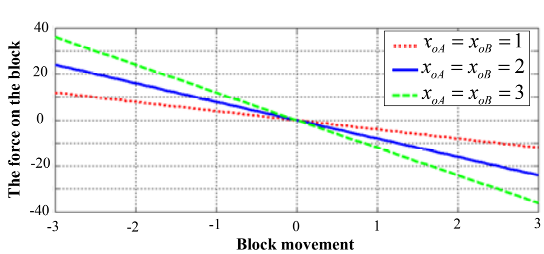

Fig. 4. The relationship between the block movement and the force on the block.

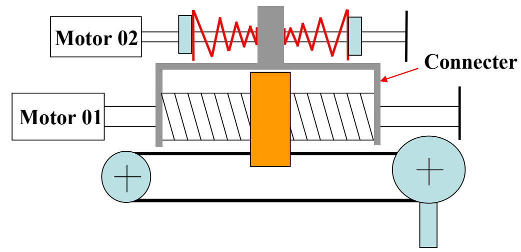

Fig. 5. A concept of an Active-Passive Variable Stiffness Elastic Actuator. Actuator.

III. Design Of An Active-Passive Variable Stiffness Elastic Actuator (APVSEA)

The two main mechanisms, a motor-ball screw system and an active-passive variable stiffness serial configuration, are designed to obtain the two desired characteristics of APVSEA, namely: accurate movement and safety in human-robot interaction.

In the motor-ball screw system, a ball screw is driven and rotated by the DC-motor01and a moving plant is placed on the ball screw. When the ball screw is rotated by the DC-motor01, the moving plant will advance or draw back in its own axial direction. There is a time belt02 fixed onto the moving plant and connected with the output link; when the moving plant moves, the output link will move and then rotate. According to the abovementioned moving structure, the APVSEA has the ability to move accurately; the 3-D model of APVSEA is shown in Fig. 6. In the active-passive variable stiffness serial configuration, a screw is rotated by a DC-motor02, and two moving plants02 move in opposite directions on the screw. There are two variable stiffness springs between the moving plant02 and connecter; when two moving plants02 are moved by the screw, the preload length of the variable stiffness springs will be changed; the 3-D model of APVSEA is shown in Fig. 7.

The APVSEA 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. The key point of the APVSEA mechanical structure is the relation between input shaft and ball screw.

In the APVSEA actuator design, an input shaft passes through the center of the ball screw. When the input shaft is driven and rotated by the DC-motor, the ball screw will be driven and rotated. When the ball screw is rotated, the moving plant, which is fixed on the ball screw, will advance or draw back in its own axial direction. There is a time belt fixed on the moving plant and connected to the output link; when the DC-motor drives the input shaft, the ball screw is rotated and the moving plant is moved. Finally, the output link is rotated because the time belt, which is connected to the moving plant with the output link, is moved. According to the abovementioned moving theories, the APVSEA has the ability to make precise position movements or trajectory tracking control easier, as shown in Fig. 8.

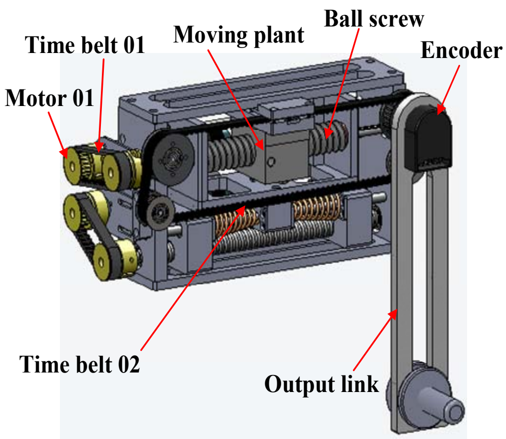

Fig. 6. 3D model of Active-Passive Variable Stiffness Elastic Actuator (APVSEA).

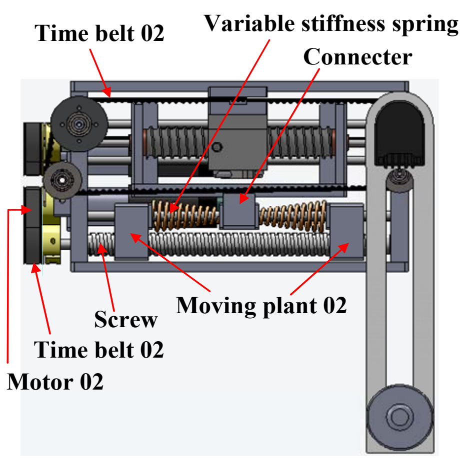

Fig. 7. Front view of Active-Passive Variable Stiffness Elastic Actuator (APVSEA).

In addition, when external forces, impacts or shocks are exerted on the output link, the external forces will push/pull the moving plant by the time belt; then all of the structures, including connecter, ball screw and moving plant will be moved. Because the input shaft goes through the center of the ball screw, the ball screw will slide in the same axial direction as the input shaft, as shown in Fig. 9. In all cases, the APVSEA has the ability to minimize large impact forces due to shocks, to safely interact with the user.

To sum up, the APVSEA can minimize large impact forces and make precise position movements; the key point is the relation between the input shaft and the ball screw. The ball screw can be rotated by the motor and makes the moving plant move. Besides, the ball screw can also be pushed/pulled by the time belt and slides on the input shaft when external forces are exerted on the output link.

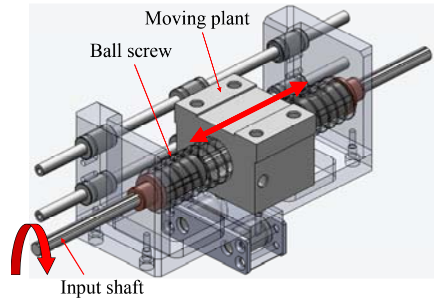

Fig. 8. 3D model of Main structure of APVSEA.

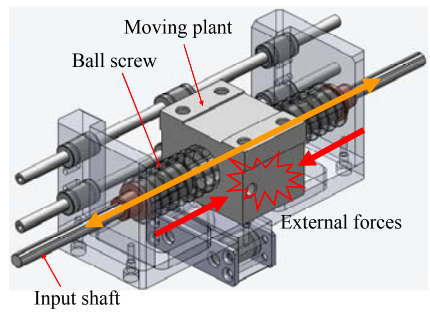

Fig. 9. 3D model of Main structure of APVSEA when APVSEA with external forces.

IV. System Experiment Evaluation

In this section, experiments were conducted to evaluate the properties and abilities of the active-passive variable stiffness elastic actuator (APVSEA). Fig. 10 is the picture of the APVSEA which consists of two DC-motors, one ball screw, one screw and four variable stiffness springs. The rotation of the axis is measured by an encoder which is fixed on the output link. Dimensions of the APVSEA, design parameters and some detailed specification are listed in the Table I.

A. *Adaptive Compliant Property*

An experiment was designed to interpret the adaptive compliant property of the APVSEA. The experiment comprises four stages. First, by using a simple PID controller, the output link of the APVSEA was rotated and kept in a vertical direction. Second, the output link of APVSEA 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 finishing position of the APVESA. The experiment shows that an adaptive compliant configuration was used to make the interaction between robots and humans safer and more natural and that APVSEA has the ability to interact with people or unknown environments under safety constrains by an adaptive compliance configuration.

TABLE I
THE SPECIFICATIONS OF APVSEA

PARAMETERS	Value
Mass (include two motors)	2.2 kg
Length*Width*Height	200*100*116 mm
DC-motor	2
Max. Output Torque	29 Nm
Max. Output Speed	24 rpm
Max. Output Link Deflection	$\pm 90^o$

* The input motors used in this prototype design are Faulhaber DC-micromotor 2642W024CR with 23/1 gear head of which reduction ration is 1:14.

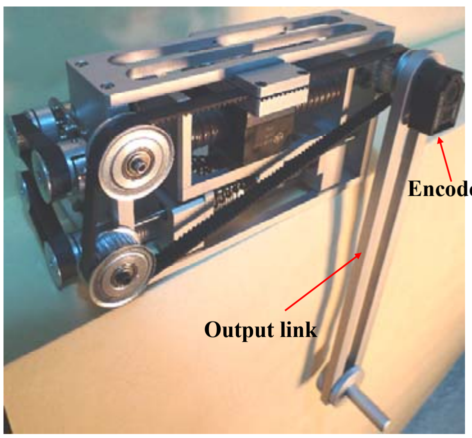

Fig. 10. Active-Passive Variable Stiffness Elastic Actuator (APVSEA).

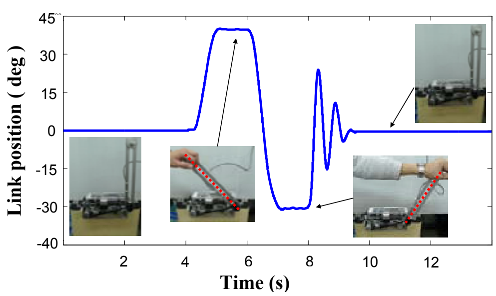

Fig. 11. Adaptive compliant property for Active-Passive Variable Stiffness Elastic Actuator.

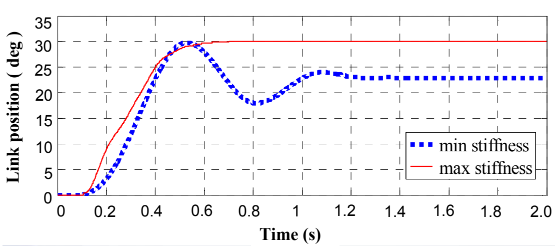

Fig. 12. Response to position command with various stiffness.

The step response of the designed APVSEA system with different preload distance of the nonlinear spring (minimum and maximum) is given in Fig. 12. The position of the APVSEA changes from 0° to 30° by using a simple PID controller; the result is a plot of the angle with time. As shown in Fig. 12, when the preload distance of the APVSEA is minimum (stiffness is minimum), vibration due to the position command over 1.4 sec and the actuator is at a 7° angle offset because of the gravity, the precise position movement ability is worse. If the preload distance of the APVSEA is maximum (stiffness is maximum), vibration does not occur, and the APVSEA has good precise position movements. The experiment shows that the APVSEA has the ability to obtain different stiffness by changing the preload distance of the nonlinear spring, and the APVSEA with maximum stiffness shows better response than the APVSEA with maximum

B. Active Variable Stiffness Property

By changing the preload distance of nonlinear springs, the APVSEA 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 a potential meter is used to measure the displacement of the nonlinear spring. As shown in Fig. 13, X_o is the preload distance of nonlinear springs. The stiffness of the APVSEA is changed with the different preload distance of the nonlinear spring.

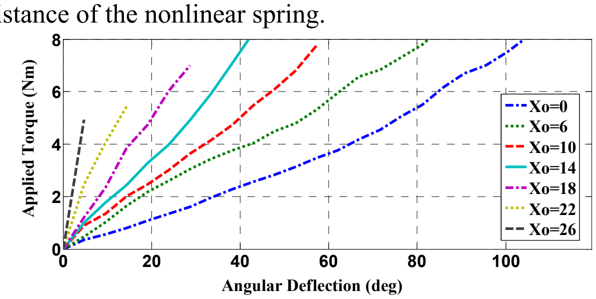

Fig. 13. Measure stiffness of the APVSEA.

C. Safe Robot System

As shown in Fig. 14, a table-tennis ball and an aluminum cube are hit by the APVSEA output link which is rotated with maximum and minimum stiffness at $2.38 rad/s$ (the preload distance of variable stiffness springs are maximum and minimum); the output link of APVSEA is 500mm long and the objects (table-tennis ball and aluminum cube) are hit at the height of 500mm. The flight distances of the objects are measured. The mean value of the flight distance data is taken after 10 measurements, as shown in Table II. The result shows that for the table-tennis ball and aluminum cube cases, the objects fly farther if the APVSEA has maximum stiffness. The stiffness of APVSEA and flight distances have been shown to be negative correlated to one another. Since the objects are static before being hit by the output link and the mass of the objects does not change, the parameter that affects the objects' flight distance is the acceleration of the objects after collision. Less stiffness leads to less acceleration of the object. Because the safety of the object depends on the objects' acceleration after collision, the experiment implies that it is safer to impact with less stiffness than with higher stiffness.

TABLE II
FLIGHT DISTANCE OF OBJECTS HIT BY OUTPUT LINK

Object	Stiffness	Flight distance
Table-tennis ball	Max stiffness	512mm
Table-tennis ball	Min stiffness	498mm
Metal block (300g)	Max stiffness	261mm
Metal block (300g)	Min stiffness	219mm

* The mean value of the data is taken after 10 measurements.

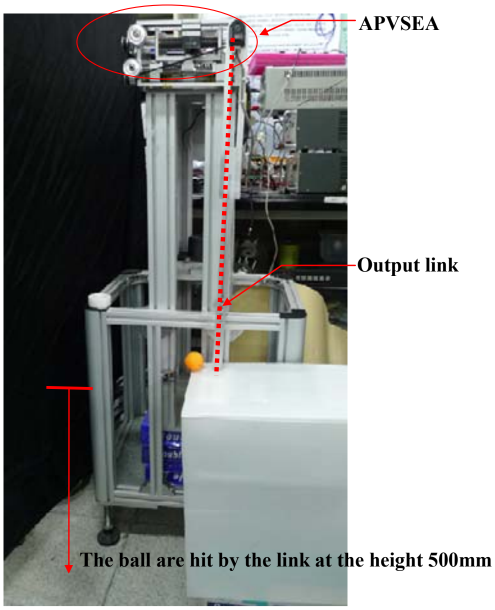

Fig. 14. Experiment setup for hitting-object experiment.

V. CONCLUSION

In this paper, an active-passive variable stiffness elastic actuator for safety robot system was presented. By changing the preload length of the two antagonistically nonlinear springs, the APVSEA 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. The preliminary results obtained from these experiments show that the APVSEA has the capability to interact with people or unknown environments under safety constrains by passive compliance, and also has the ability to obtain different stiffness by changing the preload distance of the nonlinear spring; the APVSEA with maximum stiffness shows better response than the APVSEA with minimum stiffness. When objects were hit by the output link of APVSEA with maximum stiffness, the flight distance of the object was further than in the case of APVSEA with minimum stiffness. Since, the safety of the object depends on the acceleration after the collision, the experiment showed that a joint with less stiffness was safer in case of unexpected impact with humans.

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