A Novel Mechatronic Kit of Variable Stiffness Manipulators – Design and Implementation

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Abstract. In the developing fields of wearable devices, rehabilitation, and humanoid robotics, variable stiffness actuators (VSAs) are attracting increasing attention. VSA can minimize forces that are exerted by shocks, and can be safely interacted with by their users. They can store and release energy as passive elastic elements. The main goal of this work is to design a variable stiffness mechanism with a lightweight articulated robot arm. The proposed variable stiffness mechanism is based on lever kinematics. An RC servo motor is used to manipulate the leverage and to adjust the stiffness of the mechanism to control the position of a robot arm. Two spring elements absorb the output force from the lever. Such a design can reduce the number of sensing elements that are used in the robotic system and the damage force that is caused by unpredictable external forces. The designed articulated robotic arm uses a worm gear with a 1:40 high gear ratio to increase the payload capacity and reduce the weight of the robot arm. The worm gear has a self-locking function, which reduces the sliding step of the stepping motor. The advantages of the design in this study are the retention of the strength and loading capacity of the robot arm. The software package LabVIEW is used to build the control and measurement environment in which several control syntheses are tested. Numerous experimental results confirm that the design is reliable and has a low cost of implementation in a shock test. The novel mechatronic kit is ideally suitable for use in advanced mechatronic courses for university students. The discussion of the broad issues deliberated in this investigation will be applied to various systems that require variable stiffness manipulators.

1. Introduction

Variable stiffness actuators (VSA) have attracted increasing interest in recent years as new applications of robotics that involve the interactions with an unknown and dynamic environment [1]. A VSA is a complex mechatronic device that is used to construct compliant, robust, and nimble robots. The main advantages of robotic systems with VSAs are the robustness of the mechanism, energy efficiency, agility, and dynamic performance. However, the high compliance of the structure and low intrinsic damping make control challenging.

Several researchers have developed variable stiffness actuation that is based on a mechanical system to achieve compliant motion [2-15]. In such an approach, joint stiffness is adapted to use passive elements, such as springs, to provide low stiffness and stable contact forces in the high-frequency range.

Construction of a robot with mechanically compliant joints has several goals. The main reason for joint compliance is the safety of the human operator [3]. Different hardware designs have been considered in the past to satisfy various functional demands. One review provided a guide to the
design process by analysing their effect on the selection of different components such as motors, sensors, and springs [5]. A robot manipulator with variable compliance has been designed at DLR (Deutsches Zentrum für Luft- und Raumfahrt e.V.). The first, concept-validation version incorporated many variable compliance joint designs for fingers and arms [6]. Subsequently, several researchers developed VSA robot arms that are based on the DLR variable compliance arm [6-10]. Bidirectional antagonistic variable stiffness (BAVS) has been developed and analysed [8]. Various control approaches, which include energy shaping, active/passive impedance control, and state feedback damping control, have been adapted and implemented for compliant robots [9]. An important aspect of VSAs is that their stiffness variation mechanism adds a degree of freedom (DOF) to the joint and therefore increases the system and control complexity. The joints are designed with very low intrinsic damping to make them energy-efficient and able to dissipate kinetic energy; as well as to enable elastic elements to be used to measure them torques [10]. However, variable impedance control not only supports control of the dynamic relationship between external forces and robot movements, but also provides the flexibility to change these dynamics continuously during a task [11]. Kim and Song (2012) proposed a hybrid variable stiffness actuator (HVSA) with a variable stiffness unit design. Their HVSA was composed of a hybrid control module that was based on an adjustable moment-arm mechanism and a drive module with two motors [12]. Similarly, a novel compact serial VSA with larger stiffness variation, based on a variable ratio lever mechanism [13], and a biologically inspired variable stiffness actuator that uses a variable radius gear transmission mechanism [14] have been presented elsewhere.

Many aspects of the VSA have been reviewed with a focus on the stiffness and torque characteristic of the joints. A generic port-based model of variable stiffness actuators has been developed and a conceptual design of an energy-efficient variable stiffness actuator has been implemented [15]. In most relevant studies, screw has been driven to modify the stiffness [4, 12-13]. In some, variable stiffness has been achieved by matching gears and racks to shift the position of the pivot [6-10, 14]. However, in those studies VSAs occupy a large space or the range of available stiffness is insufficient. Hence, this research develops a new variable stiffness joint for use in a robot to introduce mechanical compliance. The stiffness of the joint can be changed continuously under the maximum applied load. The rest of this paper is organized as follows. At first, this article provides an overview of the variable stiffness mechanism. In addition, measurement and control system configuration is constructed for such a system. Experimental results will present and discuss in the later section. Finally, we draw conclusions for this research.

2. System configuration

Many VSA joint designs have been provided over recent years. The main functions of the joints are similar as they enable the simultaneous control of joint torques and impedance parameters. Generally, a VSA joint features a nonlinear and variable spring torque function,

\[ \tau = k(\delta, u) \]  

(1)

where \( k \) is the stiffness function; \( \tau \) is the joint torque; \( \delta \) is the joint deflection, and \( u \) is an additional control input. Accordingly, the joint stiffness is given by, [8]

\[ k(\delta, u) = \frac{\partial \tau}{\partial \delta} \]  

(2)

The torque curve can have an arbitrary shape, and the variable stiffness is assumed herein to depend on the deflection \( \delta \).

VSAs that are based on the lever mechanism are used in three ways, which involve adjusting the location of the spring block, adjusting the location of the pivot point to change the ratio of the lever, and adjusting the point of application force [12]. Thus, the variable stiffness mechanism that is designed herein is based on the principle of the lever. In the first leverage mechanism, the pivot is located between the spring and the force point, as shown in Fig. 1(a). In the second type, the spring is located between the pivot and the force point (Fig. 1(b)). In the third, the force point is located between the spring and the pivot (Fig. 1(c)). The variable stiffness mechanism in this work is designed using the third design principle. The pivot and the spring are at the end fixed point and the force point is active. The stiffness is higher when the force point is closer to the pivot. The stiffness varies with
the lever length and spring elasticity coefficient. The proposed variable stiffness mechanism design allows for a compact structure and favorable force transmission performance.

![Figure 1. Principle of leverage.](image1.png)

Figure 1. Principle of leverage.

Figure 2(a) displays the proposed variable stiffness robot. Figure 2(b) presents the exploded view of the robot system. Figure 3 shows the variable stiffness actuator (VSA). Notably, the transmission of the VSA uses a worm gear and wheel, so the proposed VSA has a high reduction ratio and torque. It uses fewer gear sets than the traditional ones and has a compact structure. As mentioned above, many VSA joint designs have been presented in recent years but many designs need a large space or their range of available stiffness is insufficient. The VSA mechanism in this study uses gears and racks to modify the range of variable stiffness under minimal force to protect the motor from excessive loads. The main advantages of this design are its low weight and compact and robust mechanics, which allows the appropriate adjustment of the range of stiffness. Such a design can withstand an impact force in the event of a collision, minimizing damage to the robotic arm.

![Figure 2. The proposed variable stiffness robot.](image2.png)

Figure 2. The proposed variable stiffness robot.
Here, mechanical compliance is introduced by a variable stiffness mechanism, which includes a worm and wheel, a rotating shaft, a rack and pinion, a support rod and an activity pivot (Fig. 3). Figure 3(a) presents the assembly associated with such a mechanism, and Fig. 3(b) displays the exploded view.

![Variables](image1.png)  
(a) \hspace{5cm} (b)

**Figure 3.** The variable stiffness mechanism.

The variable stiffness mechanism that is proposed in this paper is based on a dual-spring design (Fig. 4). Two linear springs are assembled antagonistically on a spring shaft. When the robot arm is subjected to an impact force; the rotating shaft moves in the direction of the applied force to generate a reaction force on the support rod by shifting the position of the activity pivot. This reaction force can cause the support rod to compress the spring, which thus absorbs the external force. The stiffness of the robot arm increases with the closeness of the activity pivot to the fixed pivot of the support rod and decreases as the activity pivot moves closer to the centre of the worm wheel.

![Variable](image2.png)

**Figure 4.** Motion concept for the proposed VSA.

If the spring is squeezed with too much force as the result of a collision, the support rod and worm wheel will be destroyed. Thus, to ensure that the robot arm operates in a safe region, the safe operation mode is established. When the robot arm collides in a low-stiffness state, it is locked by the turning of the rotating shaft through 16-degrees (Fig. 5).

![Variable](image3.png)

**Figure 5.** Operation safety mode for VSA.
3. Measurement and control system configuration

To implement such a system in an experiment, a main motion control module was constructed (Fig. 6). It was composed of a PC as a master computer, a motion control card, and a human-machine interface (HMI). The Arduino Mega 2560 R3 was used as the control board. A stepping motor was used to manipulate the link joint of the variable stiffness robot system. A driver module (Model: BL-TB6560) was assembled on a printed circuit board (PCB) to drive the stepping motor. The RC servomotor (MG996R) was used to drive the activity pivot of the variable stiffness mechanism. The control system was developed using the commercial package LABVIEW. The robotic system was equipped with a set of sensors that could measure pose. The MEMS sensor module (Model: GY-521) was mounted on the proposed robot manipulator for sensing. Force sensors (Model: TAL220) were utilized as detection devices to measure the impact force from the robot link. The force transducer had a maximum sensing capacity of approximately 10 kg-w. All information data from the sensors were extracted through the Arduino Mega 2560 R3 control board to analyze their validity. Figure 6 schematically depicts the proposed control system. Figure 7 presents the experimental device.
proposed mechatronic kit can easily be made modular and reconfigurable and thus easily implemented in a university lab for use in a control course.

4. Results and discussions

4.1. Repeatability test

Performance evaluation is important in optimizing the position of the VSA robot within a workspace. A repeatability test was carried out herein to guarantee the accuracy of the VSA robot system. This test determined whether the repetitive state of the VSA robot arm was good. An indicator gauge and weighting sensing module were placed on the testing platform (Fig. 7). The VSA robot arm moved through the 90° to collide with the weighing sensor and returned to the origin five times. The root-mean-square positioning errors were approximately 0.07mm, which is very small. The worm wheel of the VSA robot arm performed a self-locking function after the collision without loss of its actuation function. These results reveal that the VSA robot arm design is reliable.

4.2. Impact test

The core feature of a VSA is the adjustability of its output stiffness. This stiffness variation can be divided into two basic interactions with the environment. One changes stiffness under constant load and the second changes stiffness at constant position. Accordingly, this subsection presents collision experiments on the proposed robot arm to test its stiffness variation. The arm is experimentally classified as having low, medium, or high stiffness. The reference stiffness position by a shift of 15mm in the support rod is shown in Fig. 8. The distance in each stiffness state is 7.5mm. Figure 9 presents the activity pivot in each stiffness state. The joint angle and impact force are measured using a GY-521 MEMS sensor and a load cell sensor module, respectively. Table 1 presents the impact force in the collision test. From Table 1, the variation of the impact force throughout the collision test is very small in all three stiffness states, in spite of the variation in initial angles. The test reveals the superior variability of the stiffness of the design. Figure 10 displays the impact force for various stiffness and initial angles. The impact force drops slowly and converges to a certain value in every stiffness state after a collision (Fig. 10).
Figure 8. The position for various stiffness.

Table 1. Impact force value for collision test.

| Stiffness States | Initial angle | Final angle | Impact force (g-w) |
|------------------|---------------|-------------|-------------------|
| High-Stiffness   | 90°           | 5°          | 737.24            |
|                  | 60°           | 5°          | 734.16            |
|                  | 30°           | 5°          | 737.37            |
| Medium-Stiffness | 90°           | 5°          | 457.54            |
|                  | 60°           | 5°          | 456.26            |
|                  | 30°           | 5°          | 454.06            |
| Low-Stiffness    | 90°           | 5°          | 249.60            |
|                  | 60°           | 5°          | 253.05            |
|                  | 30°           | 5°          | 249.43            |

Figure 9. The activity pivot for each stiffness state is indicated.
5. Summary
A novel VSA was designed and implemented. The proposed VSA mechanism uses gears and racks to modify the range of variable stiffness under minimal force to protect the motor from excessive loads. The main advantages of the design are its low weight and compact and robust mechanics, which support a favorable range of stiffness adjustment. The experimental results reveal that this innovation is reliable and has a low cost of implementation cost in a shock test. The VSA robot is also ideally suited to use in advanced control courses for undergraduate students. Therefore, the developed variable stiffness mechanism can be used to realize safe and stable robotic applications.

6. References
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