

Variable Stiffness Actuators : A General Review

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Abstract— In growing fields of robotics, rehabilitation robotics, prosthetics, walking robots and other industrial automation applications actuators are reported based on different principles. Usually these are stiff actuators creating problems of system and user safety. This problem is addressed by decoupling the inertia of actuator from the output link with the help of elastic elements resulting in lower impact forces at the time of accidents demanding the use of variable stiffness actuators (VSAs), also known as adjustable compliant actuators. To describe an actuator with a variable stiffness, the term adjustable compliance can be used i.e. variable compliance and adjustable stiffness can also be used. Compliant actuators may be grouped as passive type which can store energy and absorb shocks and active type compliant actuator which is stiff actuator controlled online by software and controller. This paper describes the review of the Variable Stiffness Actuators which are based on variable lever arm principle. These types of actuators differ from other actuators in respect to their mechanism used for stiffness variation in which stiffness regulation mechanism does not counteract the external force, resulting in lower energy consumption in stiffness regulation demanding a very small power for stiffness regulation. These actuators are mostly used due to their wide range of stiffness and ability to control stiffness and position independently.

Keywords— Variable Stiffness Actuator (VSA), Lever Arm, Variable Stiffness Mechanism (VSM)

I. INTRODUCTION

In growing fields of robotics, rehabilitation robotics, prosthetics, walking robots and other industrial automation applications actuators are reported based on different principles. Usually these are stiff actuators creating problems of system and user safety. This problem is addressed by decoupling the inertia of actuator from the output link with the help of elastic elements resulting in lower impact forces at the time of accidents demanding the use variable stiffness actuators (VSAs) also known as adjustable compliant actuators. They have an ability to absorb/minimize large forces generated due to shocks, to safely interact with other devices and the user. Also they can store and release energy in passive elastic elements. A complete review of working principles of different existing designs of such actuators is reported and compared. The designs are divided into four groups; equilibrium controlled stiffness (ECS), Antagonistic controlled stiffness (ACS), Structure controlled stiffness (SCS) and mechanically controlled stiffness (MCS). It is mentioned that the range of compliance depends on the application, as it depends on torque required by the actuators [1].

II. COMPLIANT ACTUATORS

Compliant actuators are opposite of stiff actuators. Stiff actuator is device which can track predefined trajectory and hold its position once it is moved to specific position for any external applied force, whereas compliant actuators will allow deviation from its own equilibrium position, depending on the applied external force. The equilibrium position of a compliant actuator is defined as the position of the actuator where the actuator generates zero force or zero torque.

Compliance control strategies are shown in Fig. 1. The compliance of actuators can be controlled actively and passively. In active compliance control the stiff actuator is controlled online by the use of software and controllers. It requires high performance sensors, controllers and actuators which can set stiff actuator to specific position depending on measured deviation and external force. These actuators are unable to absorb impact shocks and store energy. Instead passive compliance contains passive elastic element, which can store energy and absorbs impact shocks.

Passive compliance control is sub-divided as Fixed compliance and Adjustable compliance. In Fixed compliance category the actuator stiffness is fixed and determined by the spring selection, thus the physical stiffness cannot be changed during operation. It can control force but not natural frequency of mechanical system. In Adjustable Compliance Systems adjustment of stiffness as well as energy storage is possible. For this it requires two separate motors for position control and compliance control. Adjustable compliance Actuators have much advantages over classical Stiff Actuators for robotic and prosthetics application where variable stiffness is needed continuously.

Adjustable compliance can be obtained using various stiffness variation principles viz. Spring Preloading, Changing Transmission between Load and Spring & Changing Physical Properties of the spring.

In the Spring Preload category the stiffness is adjusted by changing the preload on the spring. The springs may be preloaded individually or by keeping it in antagonistic setup.

Drawback of this category is that, the spring force is parallel to the spring displacement; hence energy has to be stored in the springs to change the stiffness. When springs are kept in antagonistic setup the both motors should work in synchronous manner to adjust position and stiffness.

Changing transmission between load and spring category consists no spring preloading. It can be obtained by controlling parameters of lever mechanism, nonlinear mechanical link and continuously variable transmission.

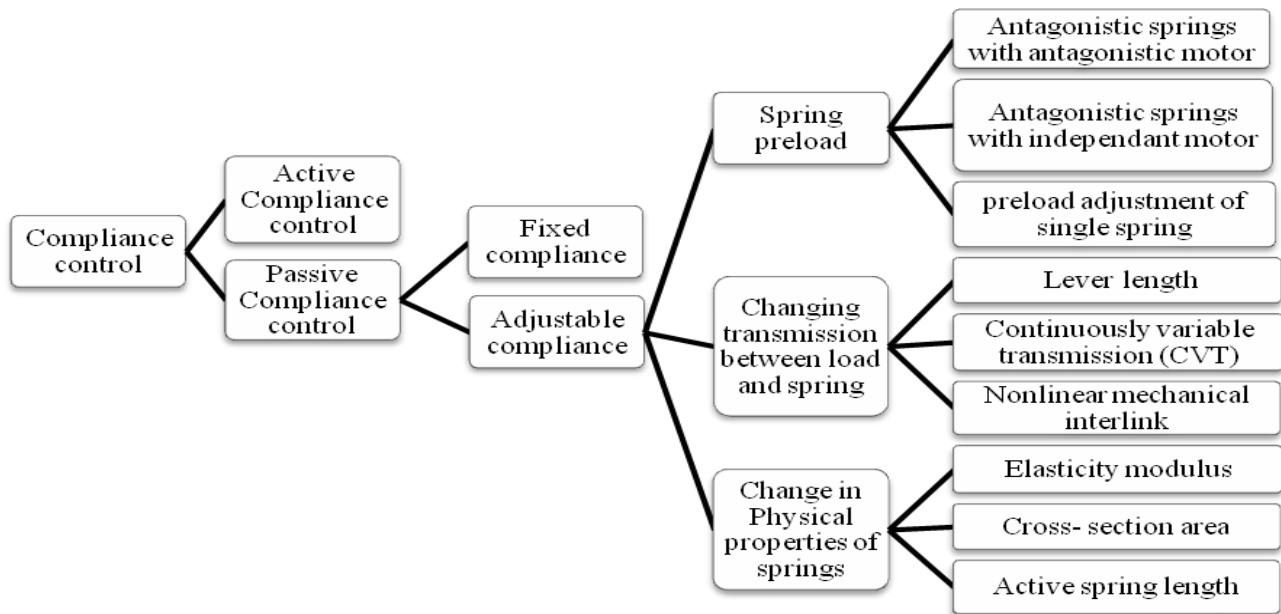


Fig. 1. Classification of compliance control.

The lever length principle includes change of three principle points of lever. In continuously variable transmission variable diameter pulleys are used to obtain different transmission ratios. In nonlinear mechanical interlink the different transmission ratios can be obtained by changing properties of links. In this group of changing transmission between load and spring the force on the spring is perpendicular to the spring displacement; therefore theoretically no energy is required at equilibrium position to change the stiffness

Change in Physical properties of springs in which any of the parameters i.e. change in modulus of elasticity, cross sectional area or active spring length is changed. Changing modulus of spring is not possible in robotic application. The c/s area can be changed by changing aspect ratio of beam and active spring length can be changed by varying number of active turns, but these activities sometimes demand power.

The compliance of actuators can also be controlled by varying damping in the system. It can be achieved by controlling friction, Rheological parameters, Eddy currents, Fluid dynamic flow properties [1, 2].

The contents of this review article are limited to study of concept of change in transmission between load and spring especially using Variable Lever Arm Length which has a very low power requirement for torsional as well as linear stiffness variation of the actuator.

III. VARIABLE LEVER ARM LENGTH CONCEPT.

Variable compliance control actuation systems usually employ two actuator units in combination with passive elastic elements to control compliance and equilibrium position of the actuated joint independently. The energy requirements for the compliance regulation depend on the implementation principle. In these systems, both antagonistic and serial configurations, the stiffness adjustment is obtained by tuning the pretension of the spring. As a consequence, the change of stiffness requires a considerable amount of energy since the actuator, which

regulates the stiffness, needs to overcome the forces due to the spring deflection. To achieve energy efficiency a new design based on Variable lever arm principle is recently used for stiffness variation. In this principle the pretension of spring is not changed instead stiffness variation is achieved by varying lever ratios.

Fig. 2 shows basic configuration of Variable Lever Arm Length concept showing three positions i.e. pivot position, force position and spring position on a lever which can be varied/adjusted to obtain variable stiffness.

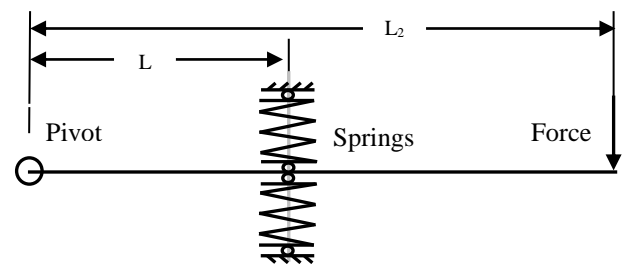


Fig.2. Basic configuration of Variable Lever Arm Length Concept

For achieving the controlled torsional stiffness about the pivot, an external arm is attached to the lever which transfers external force into lever. When the system is operated by applying force F , the angular deflection of external arm with respect to reference position determines the torsional stiffness at the center rotation of external arm.

Principle of lever arm can be categorized to vary torsional stiffness into three types namely controllable transmission ratio i) by change in spring position, ii) by change in force position and iii) by change in pivot position. These are explained below.

A. By Moving Spring Position.

Fig. 3 shows the mechanism where spring position is varied. Two springs are antagonistically attached to the lever and are able to move in linear direction with respect to the pivot point. The lever arm L_1 is defined as the distance between the pivot and the spring position. Therefore, the apparent stiffness at the joint can be changed by changing the length L_1 . When the length L_1 is changed within its range from minimum to maximum the stiffness also varies from minimum to maximum value. The range of the stiffness is defined between zero and a maximum value which depends on length of lever and spring stiffness.

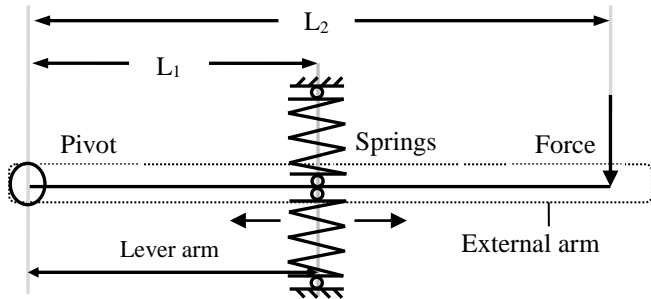


Fig. 3. Lever Mechanism with Moving Spring position.

Designs based on this principle are discussed in the following sections

1) Actuator with Adjustable Stiffness (AwAS)

AwAS has been discussed by Amir Jafari et al. [3] in detail. It consists of two different motors; one for angular position of actuator and one for stiffness variation. Main motor is connected to intermediate link. The intermediate link and output link are attached through springs. Fig. 4 shows the basic design of AwAS-I. The position of springs can be varied by ball screw drive attached on to intermediate link driven by very small motor since force is perpendicular to displacement of spring. In this concept stiffness can be achieved in a good range since it depends on the square of the Lever arm where Lever arm is considered as distance of spring position from pivot position. The range of stiffness depends on the stiffness of the springs and length of the lever. It is experimentally shown that AwAS is capable of minimizing energy consumption through exploiting the natural dynamics in real time for both fixed and variable frequency motions.

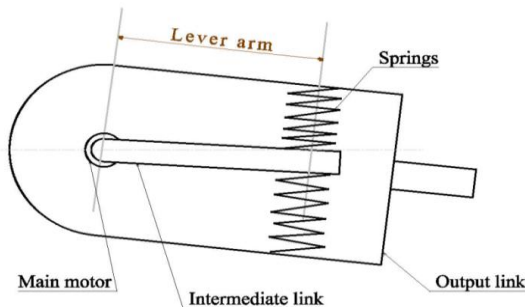


Fig.4. Schematic diagram of AwAS

2) Hybrid Dual Actuator Unit (HDAU)

Hybrid Dual Actuator Unit has been developed by Byeong-Sang Kim and Jae-Bok Song [4]. The HDAU is composed of a hybrid control module based on an adjustable moment arm mechanism and a drive module with two motors. By controlling the relative motion of gears in the hybrid control module, position and stiffness can be simultaneously controlled for the same joint. The VSM (Variable Stiffness Mechanism) of HDAU is shown in Fig. 5. It consists of a position frame, an output shaft fixed to a guide link, and two spring blocks. The hybrid control module is combination of modified planetary gear train and rack and pinion mechanism. The sun gear is replaced with dual rack gear so that planet gears will acts as planet gear and pinion gear at the same time. The linear compression spring installed at each spring block restricts the rotation of the output shaft relative to the position frame by pushing the guide link at both sides. The rotation angle of the position frame and the adjustable moment arm are the control parameters associated with position control and stiffness control, respectively.

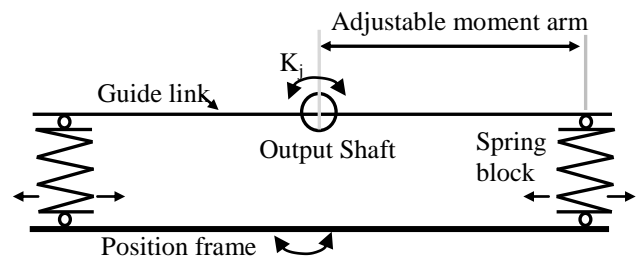


Fig. 5. Mechanism of Hybrid Dual Actuator

B. By Moving Force Position

This type of principle is shown in Fig. 6. The spring position and the pivot positions are fixed. The load position moves on the lever. The distance between load positions and pivot positions is considered as lever arm. The stiffness is varied by changing the length of lever arm. However the range of stiffness can be estimated from minimum value to infinity depending on Length of lever arm. Changing the load positions varies the output torque by keeping output stiffness unchanged.

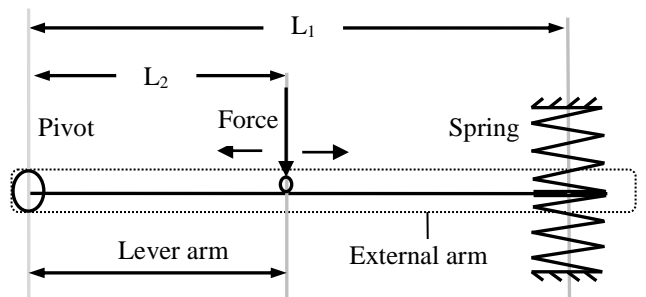


Fig. 6. Lever Mechanism with Moving Force Position.

Designs based on this principle are given in following sections

1) vsaUT

L.C. Visser et al. [5] describe a vsaUT actuator. It is based on a lever arm of variable effective length, connecting the internal (zero free length) spring to the output. In this actuator the point of application of the output force along the lever. The conceptual design of the vsaUT is shown in Fig. 7.

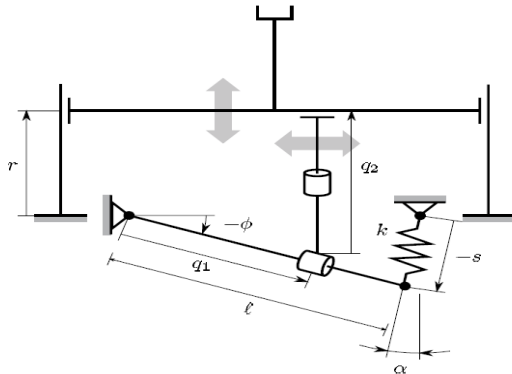


Fig. 7. Schematic diagram of vsaUT

The linear degrees of freedom q_1 , q_2 controls the lever arm length and output position of actuator respectively. In actual prototype the zero free length spring in design is generated by a pair of extension springs in antagonistic setup to the rotation axis of the lever arm. The two linear internal degrees of freedom q_1 and q_2 are actuated by spindle drives with small motors. Sliders are used for obtaining constrained motion as in design. The actuator gives translational output motion.

C. By Moving Pivot Position

This type is shown in Fig. 8. The stiffness tuning is achieved by moving pivot position while the position of springs and force are kept constant. When pivot point moves, the ratio of lever lengths changes. The ratio is taken of the distances of springs and force point from pivot point i.e. L_2/L_1 . When pivot is aligned with springs the ratio becomes zero thus the lever stiffness becomes zero, and when pivot is aligned with the load point the ratio becomes infinity thus lever stiffness goes to infinity.

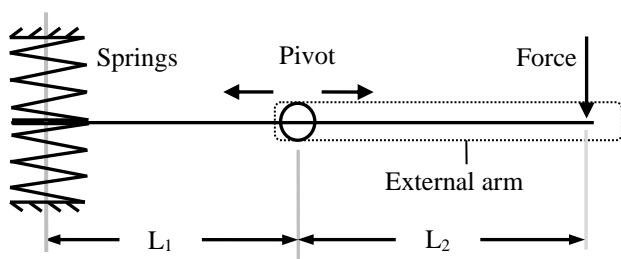


Fig. 8. Lever Mechanism with Moving Pivot Position.

This principle is used in a number of different designs because the energy required to vary stiffness is very low than other two cases of Lever [8]. Actuators based on this principle are described in the following sections.

1) Actuator with Adjustable Stiffness-II (AwAS-II)

Amir Jafari et al. [6] describe AwAS-II which is an advanced version of AwAS-I. Using the lever with moving pivot position allows the stiffness adjustment in energetically more efficient way since the parallel force which is responsible for it is very low than other two mechanisms. Therefore the stiffness motor doesn't need to directly counteract against spring's forces. The schematic diagram of AwAS-II is shown in Fig. 9. The actuator structure consists of two antagonistic torsion springs connected with a pre-deflection on one side to the output link and on the other side to one end of the lever. The other end of the lever is connected to the output link through a rotational joint. The intermediate link is rigidly attached to the main motor of the joint. The pivot is a cam follower placed within the lever and connected to the slider which is actuated by a ball screw mechanism driven by another motor. A linear guide passing through the slider prevents the rotation of slider around the ball screw and supports the later forces when the output link is deflected from its equilibrium position. When the link deviates from its equilibrium position, the end of the lever which is connected to the springs slides along the spring legs, therefore to have a frictionless sliding motion, two rollers are placed between the lever and the each springs. Since the Joint Stiffness is dependant on the ratio of lever arm length (L_2/L_1), the stiffness can be achieved from zero value to infinity. This range does not depend on the stiffness of the springs and lever's length, therefore shorter lever and softer springs can be used in this mechanism which leads to have a lighter and more compact setup compare to the mechanism applied to AwAS-I.

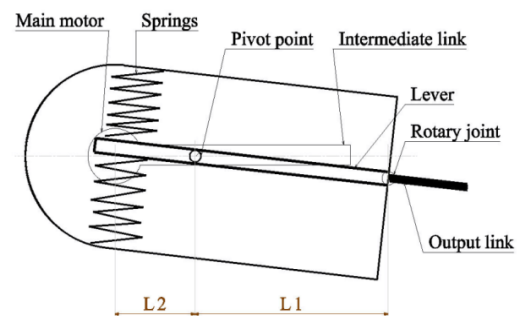


Fig. 9. Schematic diagram of AwAS-II

2) Compact variable Stiffness Actuator (CompAct-VSA)

It is described by Nikos G. Tsagarakis et al. [7]. The unit is designed to drive multi degrees of freedom VSA robotic system. This actuator uses cam shaped lever arm with variable pivot position for adjusting the stiffness resulting into compact shape of actuator and smaller time required for stiffness variation since the lever travel distance to regulate the stiffness from minimum to maximum stiffness is shorter. Stiffness variation mechanism of this actuator consists of a cam shaped lever with its pivot attached on to rack and pinion which is driven by a small motor. By changing the position of pivot with the help of rack and pinion mechanism the output stiffness can be varied, ranges from zero to infinity.

3) vsaUT-II

vsaUT-II is described by Stefan S. Groothuis et al. [8]. The main novelty of this actuator is the kinematic structure to move the pivot position along the lever arm, which is a modified planetary gears mechanism as shown in Fig. 10.

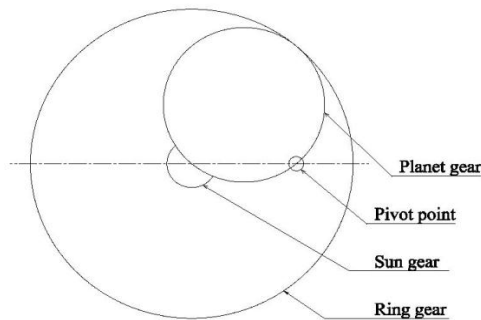


Fig. 10. planetary gear mechanism for straight line motion of pivot point on lever arm

This new mechanism to vary stiffness acquires a straight motion from only rotations this straight-line motion is achieved with a stiff, efficient and low-friction into transmission. The ring gear and planet gear are taken into precise ratio of their pitch diameters. Due to specific arrangement of planetary gears and their precise ratio between pitch diameters pivot which is attached at certain distance on planet gear moves in straight line with respect to ring gear when the planet gear runs along the ring gear. This ensures that perfect translational motion can be obtained from only rotational motion means only rotational actuators are sufficient for this. System measurements verified the model accuracy and the prototype performance.

4) mVSA-UT

This actuator is described by M. Fumagalli et al. [9]. Many designs of variable stiffness actuators are having limited range of output position but this design is having complete rotational output. The mVSA-UT is a miniaturized Variable Stiffness Actuator. This is compact and lightweight design which can change its output stiffness independently of the output position in a large range having continuous rotation of the output. The compact size is achieved by using two internal motors in differential configuration. The design of actuator can change the output stiffness without altering the potential energy stored in the springs. The stiffness altering mechanism is based on lever principle with moving pivot point. The moving of pivot in straight line is achieved by planetary gears, as proposed in case of vsaUT-II actuator. The mVSA-UT is equipped with two motors that are coupled through a differential mechanism. Smaller motor adds power at the output due to this differential mechanism.

IV. CONCLUSION

Adjustable compliant actuators play very important role in design of actuators for system and user safety. Many research publications have been reported in this context. The simplicity and energy efficient working of such devices are the key features. This can be achieved using different principles and one of these principles is to use variable stiffness actuators of simple, efficient and cost effective nature.

The torsional stiffness provided by the compliant actuator can be varied using a variable stiffness mechanism using three types namely controllable transmission ratio i) by change in spring position, ii) by change in force position and iii) by change in pivot position. Application areas for these devices are robotics, rehabilitation, wearable prosthesis.

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