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DEVELOPMENT OF A NEW MODULAR VARIABLE STIFFNESS ACTUATOR

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Abstract.*Variable stiffness actuator (VSA) is an actuator capable of changing its configuration to be stiff or compliant. VSAs have been developed to fulfill applications that require safety, energy storage and bioinspired movements. These applications include rehabilitation devices, exoskeletons, prostheses, ortheses, walking robots and any robot-human interaction. Despite that, most VSAs can't be used in a different system for which it was designed. In an academic survey it was found only one modular VSA. However, the VSA found has one limitation: it can't be coupled to existing systems that already has its motor. In this work we developed a new modular VSA that can be coupled to existing systems, whether it has or it hasn't a motor. The prototype showed in this work is a proof-of-concept and was manufactured by a 3D printer. Initial experiments showed the VSA developed is effective in adding compliance to the output shaft and its stiffness curve behaves similarly to other VSAs in the literature.*
Keywords: *modular variable stiffness actuator, variable stiffness actuator classification, creative design.*

1. INTRODUCTION

An actuator is defined as an element that moves responding to manual or automatic control (Jardim, 2009). In general most actuators are made to be as stiff as possible and their advantages are good position control and bandwidth. However, regarding safety, stiff actuators are not the best choice. Thus, Pratt and Williamson (1995) proposed the first compliant actuator called series elastic actuator (SEA). The SEA has an elastic component between motor and output shaft and is it called passive compliant actuator or variable stiffness actuator (VSA).

Since Pratt and Williamson (1995), many types of VSA were developed to fulfill applications that require safety, energy storage and bioinspired movements, including rehabilitation devices (Nunes *et al.*, 2012; Amaral, 2011), exoskeletons (Jardim, 2009; Amaral, 2011), prostheses (Au *et al.*, 2007; Klute *et al.*, 2004; Zhu *et al.*, 2010), ortheses (Blaya and Herr, 2004), walking robots (Vanderborght *et al.*, 2008, 2011; Van Ham *et al.*, 2007; Yamaguchi *et al.*, 1998) and any robot-human interaction (Tonietti *et al.*, 2005; Schiavi *et al.*, 2008; Wolf *et al.*, 2011).

Most VSAs were designed to perform specific tasks and they are limited to use in different applications. Another problem is the relative novelty of this technology and the absence of commercial prototypes (Catalano *et al.*, 2011). Nevertheless, Catalano *et al.* (2011) conceived a modular VSA with low cost that according to them can be used in many circumstances. Catalano *et al.* (2011) called the actuator developed as VSA-CubeBot. The VSA-CubeBot is a variable stiffness servo actuator and the word "servo" is used because the actuator embeds the features of a servo motor: a prime mover, a gearbox, a position sensor, an eletronic board and the algorithms to control the servo. Besides, it is possible to adjust the output shaft stiffness. Unfortunately, this actuator can't be used in mechanical systems that already have a motor.

Therefore, the authors present at this work the concept of a new modular VSA with planetary gear that can be used in previous mechanical systems linked to their motor.

This paper is subdivided by the following topics: section 2 exposes a brief bibliographic review, including concepts and classification of existing VSAs; section 3 exposes a design of the new modular VSA, highlighting its working principle and structural caracteristics; section 4 exposes initial experiments with the conceptual modular VSA and section 5 exposes conclusions, focusing on next steps of this work and future works.

2. VARIABLE STIFFNESS ACTUATOR REVIEW AND CLASSIFICATION

Actuators can be divided in two types regarding its stiffness: stiff or complacent. An ideally stiff actuator maintains its position when it collides with an obstacle or when a force is applied, within the force limits of the device (Van Ham *et al.*, 2009). A compliant actuator (complacency is the inverse of stiffness) allows deviation from its equilibrium position when it collides with an obstacle or when a force is applied (Van Ham *et al.*, 2009).

A variable stiffness actuator is capable of being stiff or complacent according to the circumstances. In general, the VSAs are divided in two big groups: active VSAs and passive VSAs.

An active VSA changes stiffness by force control between the motor and the output shaft. Some problems can occur with this type of VSA: the lowest stiffness is limited due to friction in the mechanical parts and the time delay between controller and manipulator (Nam *et al.*, 2010).

Passive VSAs have a compliant element that changes the stiffness between the motor and the output shaft (Van Ham *et al.*, 2009). This type of actuator is considered safer than active VSAs because its complacency does not depend on electronics exclusively. To simplify, the authors will refer to passive VSA as VSA only.

VSAs have intrinsic advantages such as storing energy, impact absorption and safety (Vanderborght *et al.*, 2013). However, this concept requires at least two motors: one to position control (M1) and another to change the stiffness (M2) (Vanderborght *et al.*, 2013).

2.1 VSA classification

Vanderborght *et al.* (2013) proposed a classification to VSAs regarding the stiffness changing principle and an overview of the classification is showed in Fig. 1.

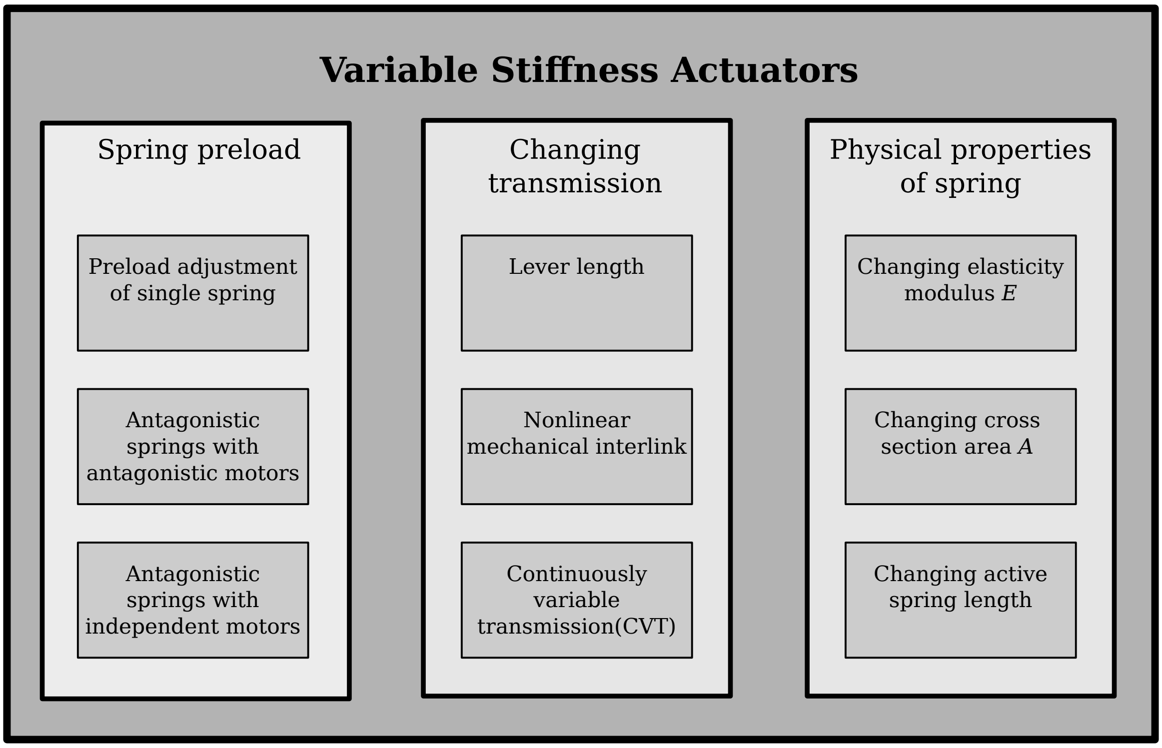


Figure 1. VSA classification. Adapted from (Vanderborght *et al.*, 2013).

The following subsections explain the classification, for examples and more details on types of VSAs see Vanderborght *et al.* (2013) .

2.1.1 Spring preload

The stiffness is changed adjusting the spring preload. This category is subdivided into three subcategories as showed in Fig. 1:

- Preload adjustment of a single spring: a nonlinear connector links the compliant element to the output shaft. In general the nonlinear connector is a cam.

- Antagonistic springs with antagonistic motors: on this configuration when the motors rotate to the same orientation the output shaft changes its position, when the motors rotate to the opposite orientation the stiffness changes. The principal limitation of this subcategory is that motors have to be synchronized to change the stiffness and the position of the output shaft.
- Antagonistic springs with independent motors: one motor is responsible for the output shaft position and another motor changes the stiffness. This concept does not require synchronization between the motors.

2.1.2 Changing transmission between load and spring

The stiffness is changed modifying the transmission ratio between the compliant element and the output shaft. This category is subdivided into three subcategories as showed in Fig. 1:

- Lever length: the lever length is composed by the pivot, the spring attachment point and the force point. By changing the position of one of these points the stiffness between the pivot and the force point (on the output shaft) is modified.
- Nonlinear mechanical interlink: this subcategory has an interlink between pneumatic muscles and the output shaft.
- Continuously variable transmission: many designs of CVTs can be used to change the stiffness between the motor and the output shaft.

2.1.3 Physical properties of a spring

To understand this category working principle consider the elastic law in equation

$$F = \frac{E \cdot A}{L_0} \Delta L = K \cdot \Delta L \tag{1}$$

Where *F* is the force, *E* is the elasticity modulus, *A* is the cross-sectional area, *L* is the effective beam length, ΔL is the beam length variation and *K* is the stiffness. The Eq. 1 shows that stiffness can change modifying *E*, *A* and L_0 (because $K = EA/L_0$) and this category is subdivided into three subcategories as showed in Figure 1:

- Changing elasticity modulus: some materials have their elasticity modulus changed, for instance, by changing the temperature. Unfortunately the response time is not fast enough and there is no known VSA example.
- Changing cross section area A: a beam with an asymmetric cross-section profile is used. The stiffness changes according to where the force is applied to deflect the beam.
- Changing active spring length: the spring stiffness is related to its active length. When the number of active coils (or spring active length) is increased, the spring stiffness decreases.

3. DESIGN OF A NEW VARIABLE STIFFNESS ACTUATOR

3.1 Modular variable stiffness actuator design

The modular variable stiffness actuator proposed here presents three degrees-of-freedom. The first degree-of-freedom is responsible for controlling the output shaft desired position (M1). As the goal is to design a modular variable stiffness actuator that will be connected to a off-the-shelf servomotor, this degree-of-freedom is left unactuated. The second degree-of-freedom changes the stiffness, increasing or decreasing the preload in an elastomer spring. This degree-of-freedom is controlled using a servomotor. The third degree-of-freedom is the elastomer spring length, this degree-of-freedom is constrained to a position determined by the spring.

The first actuator is not part of the proposed system, thus, this VSA is classified as VSA with antagonistic springs and independent motors. In this configuration, the degree-of-freedom controlled by the elastomer spring is dependent on the elastomer properties and on the first and second actuators. Thus, two approaches are possible regarding the necessary degree-of-freedom for the VSA kinematic chain.

One approach is to use a kinematic chain with mobility two and later add a spring in a manner that the spring adds a compliance between the output shaft and M1. Another approach is to consider the spring as a degree-of-freedom embedded in the kinematic chain, enumerating kinematic chains with mobility three. In this work we used the first approach, enumerating kinematic chains with mobility two.

One well-known kinematic chain with mobility two is the planetary gear. One advantage of using the planetary gear is the possibility to design the gears to achieve a desired gearbox relation. Thus, the VSA can be used as a modular system that incorporates both variable stiffness and gearbox functions.

When considering commercial modular components for servomotors, it is usual to have off-the-shelf planetary gear boxes attending different transmission ratio ranges. Regarding the variable stiffness function, different stiffness could be achieved by changing the elastomer spring and M2. Therefore, a VSA based on a planetary gear could be used as an off-the-shelf modular component easily adaptable to different ranges of stiffness and available with different transmission ratios.

As in a commercial planetary gearbox, the power input is at the sun gear. The carrier is the output shaft. The ring gear can rotate in relation to the VSA body. This rotation allows for the output shaft to have complacency, thus, the output shaft position can be different than the desired position. To achieve this complacency, a system of elastomer springs, cables and pulleys is used.

The ring gear is coupled to a connecting element. Two elastomer springs are attached to the connecting element, one at each side, adding complacency to the clockwise and anticlockwise rotations of the output shaft. Two cables are used to connect the elastomer springs to a reel. The servomotor M2 rotates the reel clockwise or anticlockwise, pulling or releasing the cables. In this manner, the preload on the elastomer spring is controlled, increasing or decreasing the perceived stiffness of the output shaft. This setup is shown in Fig. 2 together with the main dimensions.

As this configuration of springs and actuators is an antagonistic spring, the springs must present nonlinear behavior (Vanderborght *et al.*, 2013; Van Ham *et al.*, 2009). When linear springs (springs with a constant stiffness) are used in an antagonistic spring VSA, the VSA stiffness does not depend on the spring preload. Thus, any M2 actuation yields the same VSA stiffness. When nonlinear springs are used, the VSA stiffness is a function of the springs preload, allowing for adaptability on the VSA stiffness. Hence, in this design an elastomer spring was used because it presents a nonlinear behavior.

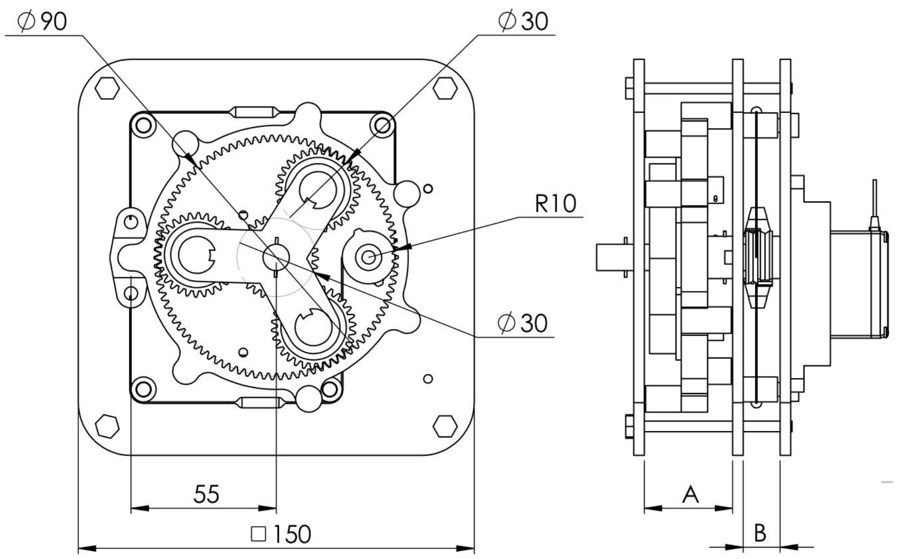


Figure 2. Proof-of-concept prototype showing its general dimensions in mm. The planetary gear is in the "A" layer and the stiffness control mechanism is in the "B" layer.

3.2 Proof-of-concept prototype manufacturing

A proof-of concept prototype was manufactured. The gears, pulleys and reel were 3D printed in ABS material using GTMax3D Core A1 3D printer. $4\ mm$ laser cut acrylic sheets were used to support the pulleys, gears and servomotors. An unbranded MG996R 1.27 N.m (13 kgf.cm) at 4.8 VDC servomotor was used as M2 to control the VSA stiffness. A SM-S4306R 360 degree was used to simulate a servomotor to which the modular VSA would be attached. The servomotors actuation are controlled by an Arduino Uno R3 and two 100 kΩ linear potentiometers. An Ultra-high-molecular-weight polyethylene cable with a 177.93 N (40 lbf) strength was used to preload the spring. Figure 3 shows the prototype and its main components. Figure 4 shows the electronic circuit used to control the prototype.

4. RESULTS AND DISCUSSION

The modular VSA prototype was submitted to initial experiments to verify the stiffness behavior. The experiment consisted of applying a known load of 500 g on a 75 mm lever connected to the VSA output shaft resting in a horizontal position. This load resulted in a torque (τ) of 368.25×10^{-3} N.m (3.75 kgf.cm) applied on the output shaft. The degree-of-freedom from the elastomer springs allows the output shaft and the ring gear to rotate together. These components rotate

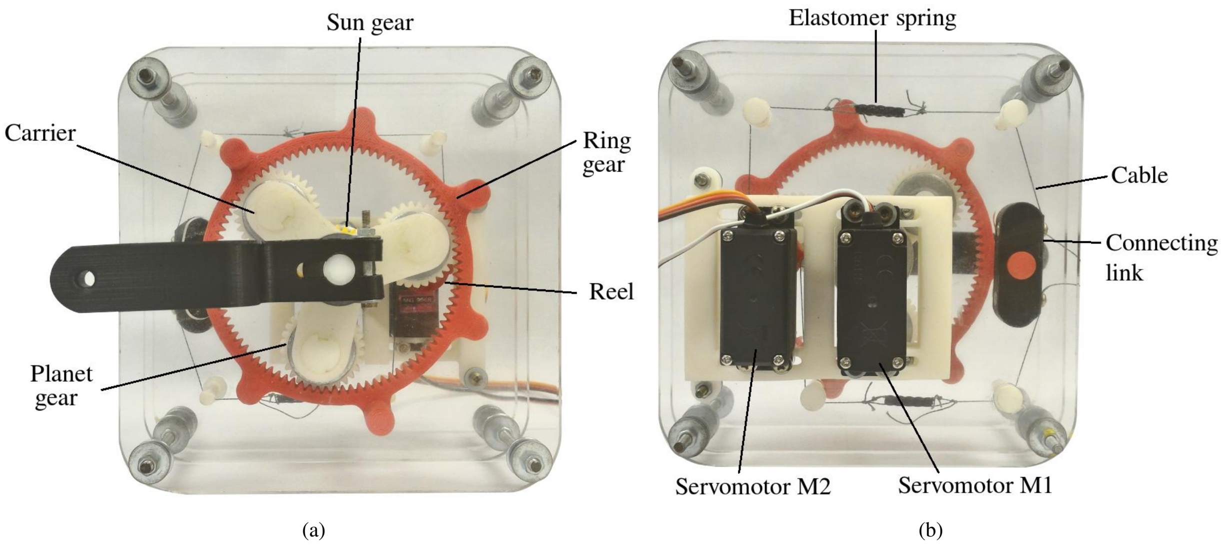


Figure 3. Proof-of-concept prototype manufactured in a 3D printer with its main components labeled.

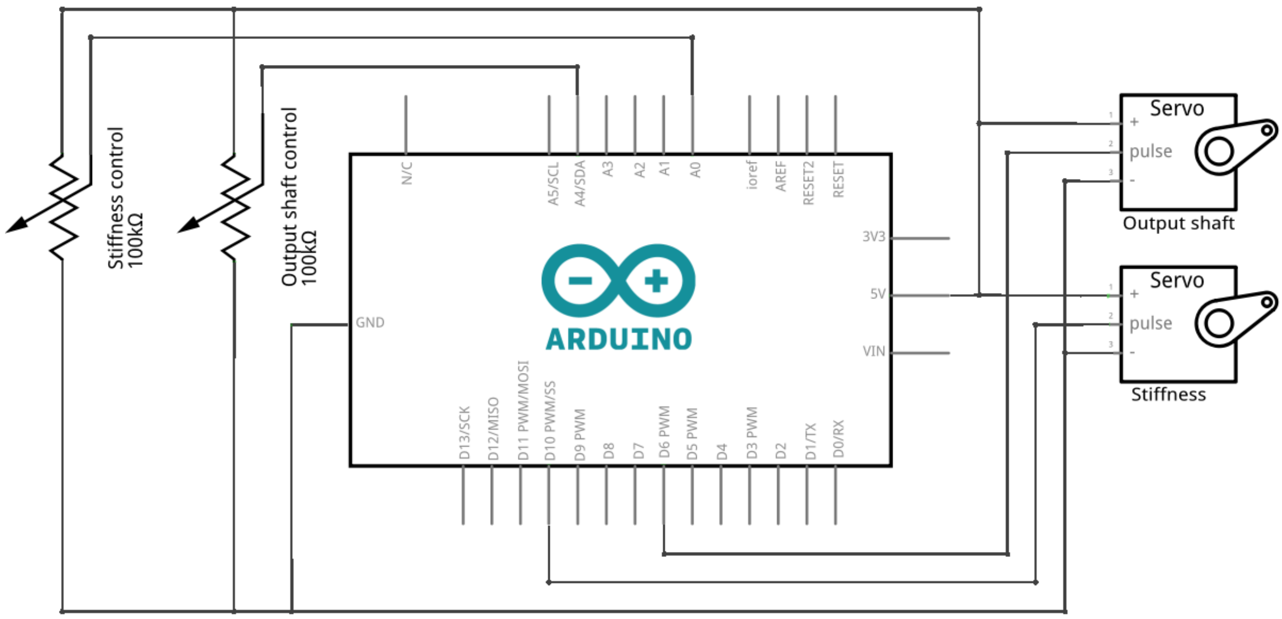


Figure 4. Control platform schematic composed of an Arduino Uno R3 development board, two servomotors and two potentiometers.

until the elastomer spring displacement generates a torque on the ring gear with the same value of the torque applied on the output shaft, achieving static equilibrium.

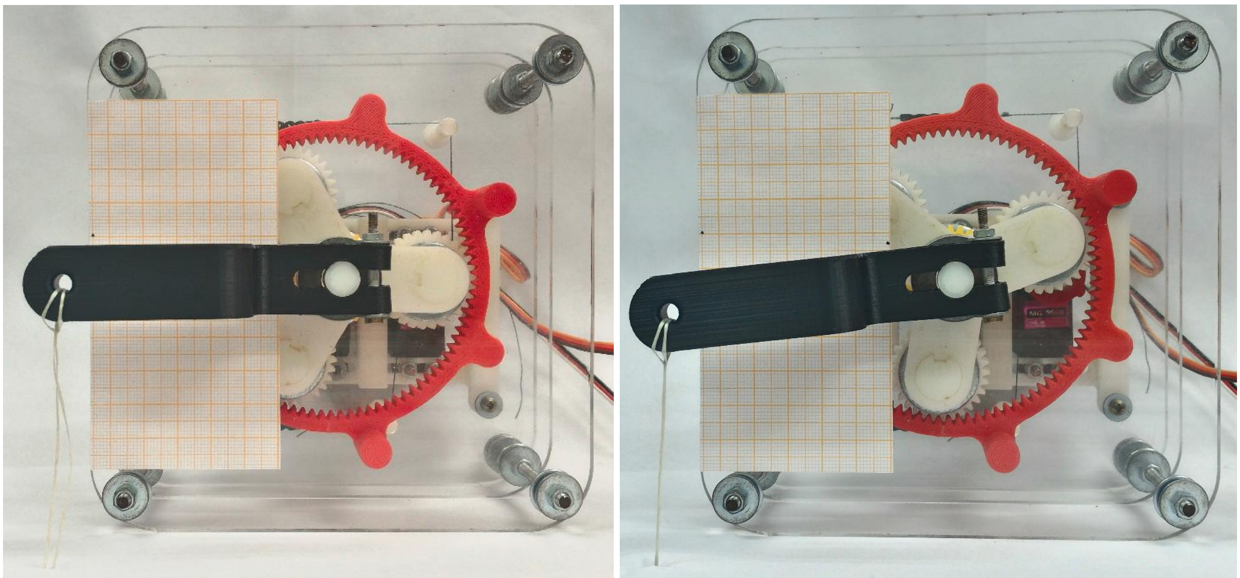
Several measurements were taken with different preload on the elastomer spring. The following steps were repeated for each measurement:

1. the lever attached to the output shaft was positioned at horizontal position, no load was added at the lever on this step. Figure 5a shows the VSA at this initial setup.
2. The elastomer spring was preloaded, measuring its length.
3. The load was applied on the lever, a picture was taken using a camera mounted on a fixed position. Figure 5b shows the VSA at this step.
4. The load was removed from the lever.

Several measurements were taken, changing the elastomer spring displacement from 0 mm to 8 mm. The lever angular displacement ($\Delta\theta$) was calculated for each photo. The VSA stiffness (κ) for each different elastomer spring preload was calculated as

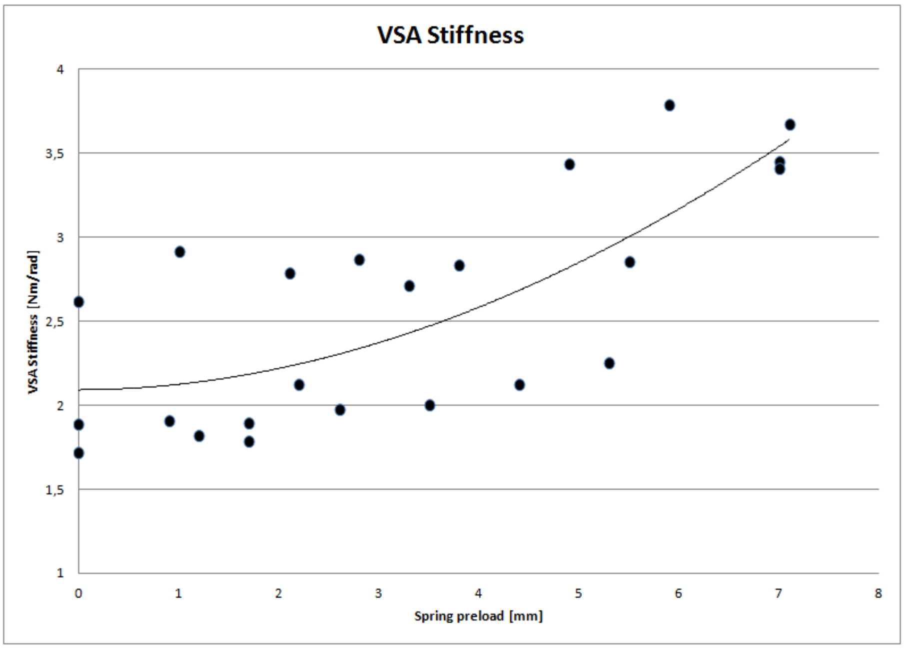
$$\kappa = \frac{\tau}{\Delta\theta}, \tag{2}$$

The VSA stiffness as a function of the elastomer spring preload is shown in Fig. 6.



(a) (b)

Figure 5. Angular displacement during the experiments. (a) initial setup. (b) lever displaced after the load was applied.



(a)

Figure 6. VSA Stiffness as a function of the elastomer spring preload.

The initial experiment shows that the stiffness of the prototype tends to increase with the spring preload in a non-linear behavior. This dependence of the VSA stiffness on the spring preload indicates that the concept proposed is a valid solution for a VSA. The non-linear behavior of the VSA stiffness as a function of the spring preload is in accordance with other antagonistic springs and independent motors configuration found in the literature (Jafari *et al.*, 2010; Vanderborght *et al.*, 2011). During the experiments it was not noticeable any signs of plastic deformation of the elastomer spring, even after applying 50 percent of its original length as preload, which indicates that the maximum stiffness of the prototype while operating in the elastic domain of the elastomer is higher than 3,5 (Nm/rad).

5. CONCLUSIONS

This paper presented a novel variable stiffness actuator. This modular actuator can be attached to existing systems, adding variable stiffness and gearbox features in one module. A proof-of-concept prototype was manufactured. Initial experiments showed the proposed VSA is effective in adding compliance in a controlled manner to the output shaft.

The experiments showed the modular VSA stiffness curve behaves similarly to other VSAs in the literature. A dimensional synthesis is required in order to obtain the dynamic analysis of the modular VSA. With the dynamic analysis there will be a better knowledge of the stiffness behavior.

As future works, we expect to redesign the variable stiffness module so servomotor M2 does not require power input to maintain a desired stiffness and only requires power to change the stiffness. We expect to design a VSA to a specific application, doing the dimensional synthesis and dynamic analysis, optimizing the transmission ratio and variable stiffness module. Additional tests are expected to be carried out as well as a dynamic analysis.

6. ACKNOWLEDGEMENTS

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