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Single Motor–Variable Stiffness Actuator using Bistable Switching Mechanisms for Independent Motion and Stiffness Control

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Abstract— **This paper presents a proof of concept of a variable stiffness actuator (VSA) that uses only one (high power) input motor. In general, VSAs use two (high power) motors to be able to control both the output position and the output stiffness, which possibly results in a heavy, and bulky system. In this work, two small and light-weight clutches are used to lock either one of the degrees of freedom, allowing the other to be controlled by the input motor. These clutches are realized by friction belts that can engage to a surrounding cylinder. The clutches are operated by solenoids, and small bistable mechanisms ensure that no electrical energy is lost in keeping a degree of freedom locked or unlocked. An experiment with a prototype of the system is performed which validates the proof of concept of this Single Motor–VSA.**

I. Introduction

The time that robots are only used in highly structured and known industrial environments, which requires them to be very stiff, accurate, and precise (consistent), has passed. In current and future research, there is a clear goal to develop robots that are capable of safely interacting with humans, so that robots can work for or cooperate with humans. This means that robots need to be able to function in highly unstructured and unknown environments. The need for safe human robot interaction has led to a paradigm shift of fast, high-bandwidth, and stiff robotic systems, to slower, and (active or passive) compliant systems. These compliant systems ensure safe behavior, because they can deflect upon interaction or collision with an obstacle, i.e., they show soft behavior. Within this paradigm, various safety measures have been developed, among which are VSAs, that are capable of varying their connected load position as well as the compliance that couples the motor to the load. These VSAs can be used as the joints in robotic mechanisms to enable safe and compliant actuation. Many different designs have been proposed in the literature, and most of them make use of mechanical springs. They can be classified in three major groups [1]: the spring preload group [2], [3], [4], the group in which the transmission between load and spring is changed [5], [6], [7], [8], and the group of changing physical spring properties [9], [10], [11].

These VSAs require two (not necessarily equally) powerful motors to control both the output position and the output stiffness degree of freedom. This means that the device is likely to become bulky and heavy, since powerful motor and gearbox combinations add considerable weight and volume to a system. This is shown for the group of VSAs with variable transmission or variable physical spring properties in Figure 1, where two input motors are necessary to control the two degrees of freedom of the variable stiffness mechanism: one for the equilibrium output position and the other for the stiffness. Being able to control both the output position and stiffness with only one motor reduces the weight and volume, which can be achieved by switching between degrees of freedom using, for instance, clutching mechanisms.

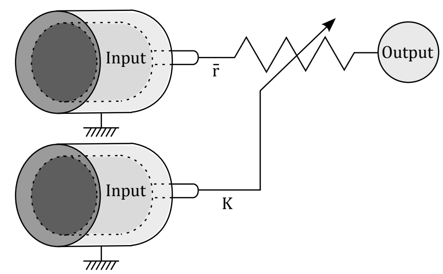

Fig. 1: Typical VSAs use two motors for motion and stiffness control.

Clutching mechanisms in compliant actuators have been proposed earlier. In [12], a clutching mechanism was used in parallel to a driving motor to create both a series elastic actuator (SEA), with a disengaged clutch, and a passive compliant joint, with an engaged clutch. Similarly, in [13] and [14], a clutch mechanism placed in parallel to the elastic element was used to lock a joint in a rigid, high-bandwidth operational mode, while disengaging, or slipping, the clutch to ensure compliant interaction. In [15], a series clutch actuator was proposed, which uses electronically adjustable friction clutch discs to limit the applied force at the end-effector to a prescribed safe level. Exceeding that level causes the clutch to slip. In [16], these clutches where used to provide friction to brake an artificial muscle-driven joint. In other previous work [17], One-To-Many actuators have been presented, in which one electric motor can charge multiple elastic element modules, that can then release the stored potential energy as kinetic energy on multiple outputs. This means that the energy delivered to the output never exceeds the energy that is present in the elastic elements since the input motor is never directly connected to an output. This is desirable for stability and safety, but not desirable if more energy needs to be supplied to an output than the limited amount that is stored in the elastic element.

In [18], a prototype of a VSA was developed that could switch between operational mode (either position change, or stiffness change) using an auxiliary motor to drive a clutching mechanism. The main motor was then able to actuate both

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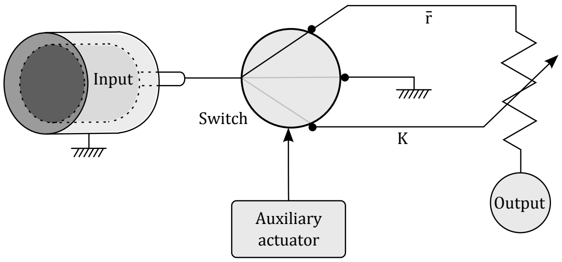


Fig. 2: Schematic representation of a switching VSA. The input motor is coupled by a switch as position control or stiffness control. The switching is done by an auxiliary actuator.

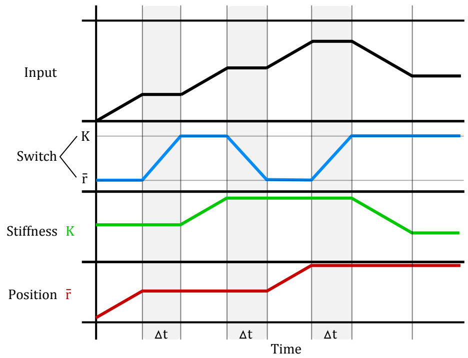


Fig. 3: An arbitrary input motor and switching profile, together with the resulting stiffness and position changes. The switching between operational modes takes some time Δt during which the motor is stopped.

degrees of freedom separately. However, switching between operational modes took approximately 20 seconds making that prototype only usable for a very limited number of, mainly slow-moving, applications.

This paper presents a Single Motor–Variable Stiffness Actuator (SM–VSA) which uses only one high-power input motor, while it is capable of actuating two degrees of freedom. It is shown that switching between the operational modes is near instantaneous, because of the usage of solenoid-driven bistable mechanisms. In the SM–VSA, the input motor is directly connected to one of the degrees of freedom, so the limitation of the finite amount of energy that can be supplied to an output in one actuation phase, is not present.

This paper is organized as follows: the conceptual analysis of the novel Single Motor–VSA is presented in Section II. Then, the design and prototype of the SM–VSA are treated in Section III. An experiment with this prototype is done and is reported in Section IV. The results are discussed in Section V and the paper concludes with Section VI.

II. Conceptual Analysis

Figure 2 shows a schematic representation of the SM–VSA. It consists of one input motor that is coupled to a switching mechanism. This switching mechanism determines whether the input motor is coupled to a mechanism that controls position, or that controls stiffness. This switching is done by an auxiliary actuator which is never directly coupled to the output and its attached load. The motor can also be coupled to the fixed world, to allow a transition phase. The procedure of switching between position and stiffness control is shown in Figure 3, in which an arbitrary motor input profile and an arbitrary switching profile, together with

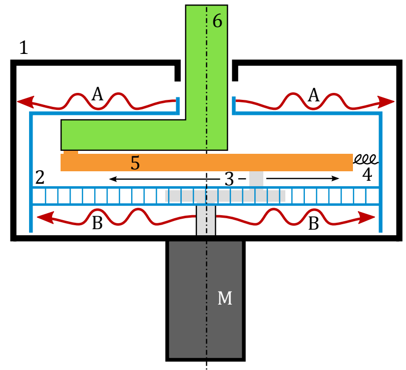


Fig. 4: A schematic cross section of the novel SM–VSA, which is based on the mVSA-UT [19]. It consists of a frame (1), a rotor (2), a planet carrier and gear with pivot (3) — which forms, together with a ring gear on the rotor (2), the gear mechanism to change the stiffness —, a spring (4), a lever (5) and an output (6). Depending on the state of clutches (A and B), that can couple rotor (2) to frame (1) and planet carrier (3) to rotor (2), respectively, the motor (M) can either actuate the equilibrium output position, or the output stiffness.

the resulting stiffness and position are shown. At first, the switch couples the input motor to the position change (the equilibrium output position $\bar{r}$), resulting in an increasing equilibrium position. Then, the input motor stops and the switch takes a certain amount of time Δt to change from position mode to stiffness mode, after which the motor can be enabled again, resulting in a stiffness change. The second and third Δt regions show a similar mode switching procedure.

The SM–VSA is based on the integrated and miniaturized mVSA-UT [19], which in turn is based on the vsaUT-II [8]. The variable stiffness on the output is realized by using a variable transmission ratio between the internal springs and the output. This transmission ratio is varied by moving a pivot along a lever arm using a hypocycloid gearing mechanism. Figure 4 shows a cross section of the SM–VSA. There is one central motor (M) and the frame (1) is attached to its housing. The rotor (2) is the degree of freedom that sets the equilibrium output position. Inside this rotor, the gear mechanism is found which consists of a ring gear (connected to the rotor) and a planet carrier with planet gear and pivot (3), which rotate in the ring gear, and thereby move the pivot in a straight line along a lever (5), which rotates around the pivot. Springs (4) are attached to this lever, and the output (6) is connected on the other side of the lever.

The novelty in this design lies in the clutches A and B. Clutch A can connect (and lock) the rotor (2) to the frame (1), while Clutch B can connect (and lock) the planet carrier (3) to the rotor (2). The degree of freedom that can be actuated by the motor (M), depends on which clutch is engaged. Table I reports the various configurations and resulting situations of the SM–VSA. Note that since there are two clutches, the operational procedure is slightly different from the one that is graphically depicted in Figure 3.

III. The Novel Single Motor–VSA

A. Bistable switching mechanism

1) Friction belts: There are two clutching mechanisms in the SM–VSA to be able to switch between the motion or stiffness degree of freedom. They make use of friction

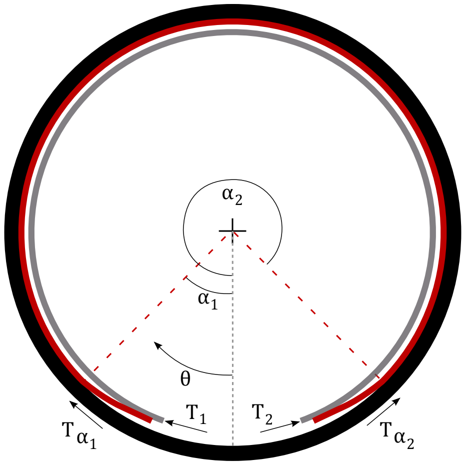
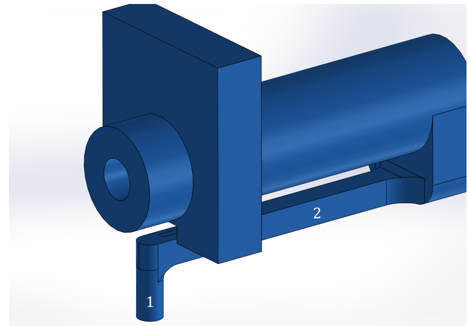


Fig. 5: View of the friction belt inside a cylinder. The symbols are belt tension T, angles of engagement α_1 and α_2, and circular coordinate θ.

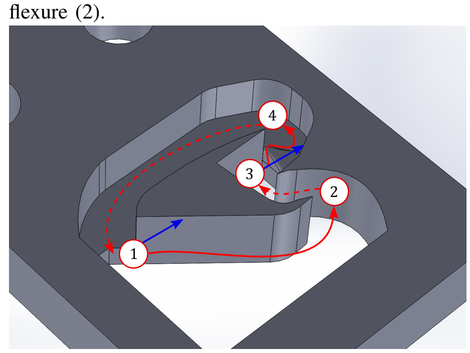
belts that expand in diameter to engage to a cylinder directly surrounding it. Friction belts are inexpensive and simple, can be small and light-weight, and can be manufactured easily allowing rapid prototyping techniques [20]. A friction belt inside a surrounding cylinder is shown in Figure 5. This friction belt should be a slightly flexible open circular shape of which the diameter can be enlarged by applying a force at both open ends (T_1 and T_2). This causes the friction belt to engage uniformly in a surrounding cylinder at angles α_1 and α_2, thereby causing friction which blocks the rotation of the friction belt in the cylinder. Note that the friction belt should not buckle, since no tension can be built up in the belt and it does not engage to the cylinder uniformly.

2) Auxiliary actuators: The auxiliary actuators should be translational actuators to generate the forces T_1 and T_2 that are necessary to enlarge the friction belt, as shown in Figure 5. The actuators should preferably be electric, so that the control system and the prototype itself are simple and straight-forward without needing much additional equipment. Therefore, pneumatic actuation, for example, was not considered. Piezo stacks or piezo benders deform when an electric field is applied (or vice versa). This deformation can be directly used to engage or disengage the clutch. Although these piezo elements can deliver much force when a high voltage is applied, their stroke or deformation is very limited, i.e., often less than a millimeter. Therefore, solenoids (Kuhnke HU 244) are used as auxiliary actuators, to generate the force that is necessary to enlarge the friction belt. They can deliver high forces with acceptable strokes and are relatively small, which allows an easy integration.

3) Bistable switches: The friction belts are the clutches to lock or unlock degrees of freedom, for which a continuous applied force is needed. It is not desirable to use the solenoids to directly generate this force, since this requires electrical energy, while no mechanical work is performed. Therefore, a bistable mechanism was used to keep the friction belt in either the locked or the unlocked state. The bistable mechanism, shown in Figure 6, is inspired by one of the many mechanisms that can be found in a ballpoint pen. It uses a cam follower (Figure 6a) and a cam profile with two stable positions (Figure 6b).



(a) A pin-shaped cam follower (1) attached to a flexure (2).



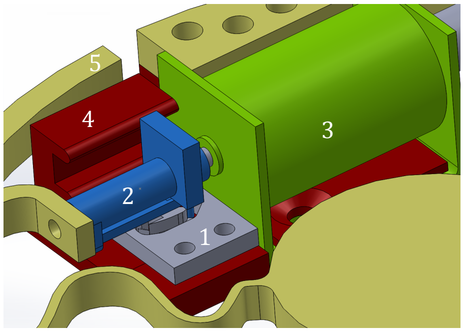
(b) The cam in which the cam follower moves, with stable position (1) and (3), and intermediate position (2) and (4). The red solid line shows actuated movement, while the dashed line indicates relaxation movement.

Fig. 6: The bistable mechanism consists of a cam profile and a cam follower.

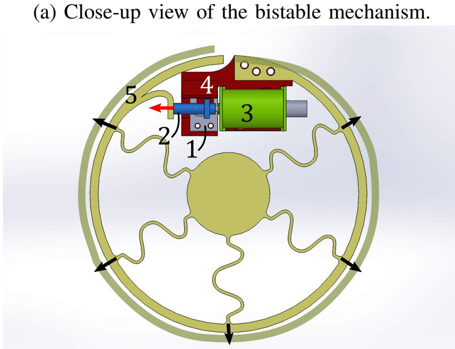
The pin-shaped cam follower is unloaded at position (1) in Figure 6b. When a force is applied (blue vector, representing the solenoid force), the flexure of the cam follower deflects and the pin moves to position (2). When the force is removed, the loaded flexure causes the pin to move to stable position (3). When again a force is applied in the direction of the vector, the pin moves to position (4), and when the force is removed, the enlarged and therefore loaded friction belt (pushing the cam follower in the opposite direction of the force vector shown) causes the pin to move to position (1) again. Figure 7 shows the complete assembled bistable mechanism with friction belt. If the solenoid is powered very

TABLE I: Various configurations of the novel Single Motor–VSA in Figure 4, as a result of an engaged or disengaged switching mechanism state.

	A engaged	**A disengaged**
B engaged	Fully locked configuration. The motor cannot move, the output can deflect passively.	The motor moves the equilibrium position, while the stiffness change is locked (constant stiffness). The output is actuated and can deflect passively.
B disengaged	The motor moves the planet carrier, thereby changing the stiffness. The equilibrium position is fixed to the frame and the output can deflect passively.	This is an underdefined situation. The motor moves the planet carrier, but the rotor (2) is also free to move. The output can deflect passively, but may also backdrive the rotor (2). This situation is *not* desirable and should be avoided.



(a) Close-up view of the bistable mechanism.



(b) Top view of the bistable mechanism, showing the expansion of the friction belt.

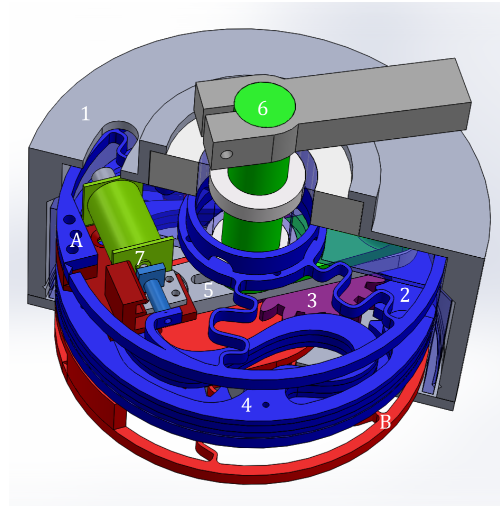
Fig. 7: The assembled friction belt with bistable mechanism and solenoid. The labels refer to the cam (1), the cam follower (2), the solenoid actuator (3), a bracket for assembling (4), and the friction belt (5). If the solenoid is powered, it pushes the cam follower (red arrow) from the first stable position through the cam profile into the other stable position, causing the friction belt to expand (black arrows).

briefly (red arrow), the friction belt enlarges (black arrows) and stays enlarged. No electrical energy is consumed to keep the mechanism in this state. When the solenoid is powered again, the friction belt returns to its initial state. Five flexures attached to the friction belt can be seen. These flexures are chosen such that they allow the friction belt to expand radially, while preventing it from moving out of plane.

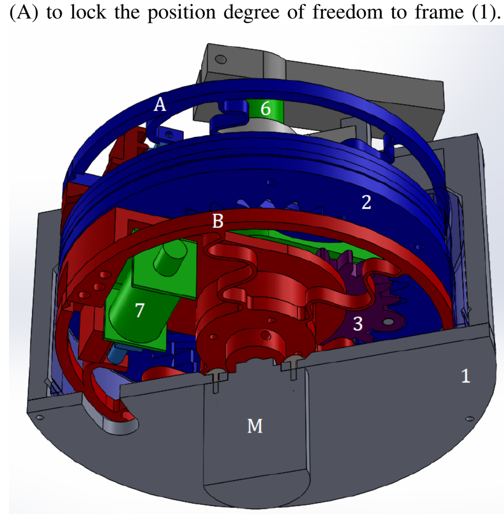
B. The Single Motor–VSA Design and Prototype

A cross sectional view of the SM–VSA is shown in Figure 8, and an exploded view of the SM–VSA is shown in Figure 9. The numeric labels, identical to the ones in Figure 4, refer to the frame (1), the rotor with attached ring gear (2), the planet gear on top of the planet carrier (3), the (leaf) spring (4), the lever arm with groove for the moving pivot (5), the output with output arm (6), and one of the two bistable mechanisms (7). Both friction belts (A and B) can be distinguished. Friction belt (A) and the corresponding bistable mechanism with solenoid rotate together with rotor (2) inside frame (1), when the clutch is not engaged to frame (1). Likewise, friction belt (B) and the corresponding bistable mechanism rotates together with the planet carrier (3) inside rotor (2), when the clutch is not engaged to rotor (2).

A prototype of this system was manufactured, using rapid prototype techniques, i.e., laser cutting and 3D-printing. The finished prototype is shown in Figure 10. The frame, indicated with (1), was 3D-printed and has a diameter of 120 mm and a height of 64 mm. Including the output (6), which was also 3D-printed, the height is 99 mm. Furthermore, the



(a) Top view, with bistable mechanism (7) and friction belt (A) to lock the position degree of freedom to frame (1).



(b) Bottom view, showing bistable mechanism (7) and friction belt (B) to lock the stiffness degree of freedom.

Fig. 8: A CAD drawing of the SM–VSA, where the labels are similar to those in Figure 4. The frame, or housing, is indicated with (1), the rotor (2) consists of an enclosing frame (shown transparent) within housing (1) connecting the ring gear, (leaf) spring (4), and friction belt (A), a planet gear with pivot (3) sits on a planet carrier to which the second friction belt is connected (B), the lever arm (5) connects the springs to the output (6), and the friction belts are actuated by the bistable mechanisms (7).

rotor, the lever, the planet carrier, the cam and cam follower were 3D-printed as well. The friction belts, the springs, and all gears were laser cut from plastic. Friction tape was put on the friction belts to increase the friction coefficient. The solenoids are powered using a custom charge and discharge circuit, in which a $C = 30$ μF capacitor is fully charged in 200 ms, and discharges over the particular solenoids used in 20 ms. When it discharges, it is ensures that the power supply is disconnected from the capacitor, so that never more charge than what is in the capacitor will be released through the solenoid to prevent overheating. A supply voltage of $U = 130$ V ensures a proper operation of the bistable mechanisms by the solenoids. This means that the energy to switch between operational modes, which requires switching operation in both mechanisms, is $2 \cdot E_{\text{switch}} = 2 \cdot \frac{1}{2}CU^2 \approx$

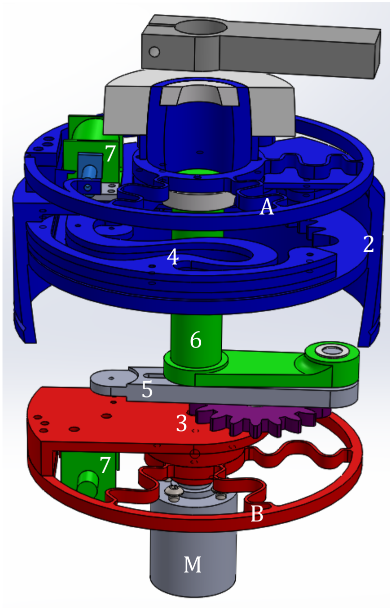


Fig. 9: Exploded, and partially cross-sectional, view of the SM–VSA, with the same labels as in Figure 8. The enclosing frame of the rotor (2), and the planet carrier (3) to which the planet gear of the gear mechanism is connected are now shown more explicitly.

0.5 J. In principle, it would then take 40 ms.

IV. Experimental Validation

An experiment was performed with the prototype of the system. An Arduino was used as software platform. The SM–VSA can be controlled with two buttons, to power the two solenoids, and a potentiometer to set the velocity of the input motor. The motor has an incremental optical encoder for measuring its position and velocity and an absolute magnetic encoder was used to measure the output angle. The motor is controlled in velocity mode and the Arduino communicates with the motor controller to set and measure the position and velocity. The Arduino sends the measurements of the encoders and the states of the buttons to Matlab Simulink (The Mathworks, Inc., Natick, MA, USA) through a serial RS232 connection. In Simulink, the data is acquired and passed on to the workspace for further processing.

The experimental result is shown in Figure 11. It starts with a locked stiffness degree of freedom (so the stiffness is constant, at the stiffest setting), while the motion degree of freedom is unlocked. The motor is then turned, which moves the output as expected. Then the motion degree of freedom is also locked, to ensure that the system remains in the current configuration and does not become underdefined, after which the stiffness degree of freedom is unlocked. In this experiment the switching was done slowly (the grey shaded area is approximately 2 seconds wide), which was done to clearly indicate the switching sequence. In principle, this can be done in 40 ms. The motor is then turned again during interaction with the output (manually tapping), which results in an oscillation-like behavior with growing amplitude, because of the decreasing stiffness (increasing compliance). When the most compliant setting is reached, the stiffness degree of freedom is locked again, the motion

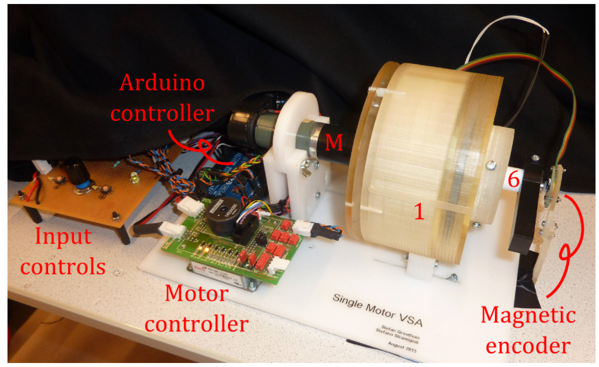


Fig. 10: Prototype of the novel Single Motor–VSA.

degree of freedom is unlocked and the motor then rotates the output again. Some interaction occurs, showing that the output compliance is properly kept. In the video attachment to this paper, this specific experiment can be seen.

V. Discussion

The experiment validates the proof of concept: it is possible to control both degrees of freedom of a VSA with only one input motor. Obviously, there is always a need for more than one actuator to be able to do this, but the two auxiliary actuators that are needed in this prototype to switch between degrees of freedom, are small, light-weight, and only briefly powered to lock or unlock a degree of freedom almost instantaneously. This means that one high power, and relatively large and heavy motor is sufficient and no additional high power motors are necessary.

The prototype has been designed to have the ability to manufacture with rapid prototyping facilities. This means that the focus was put on an integrated cylindrical design that features two mechanical interfaces, i.e., the input motor and the output shaft, and not so much on having the most compact design. An issue with the current design is that continuous rotations are not possible because of wires going to the solenoids. However, slip rings that transmit electrical power to the rotating elements easily solve this problem.

Traditional VSAs are capable of simultaneous actuation of position and stiffness, while this prototype is not. Here, only one of the two degrees of freedom can be actuated, which would suit applications in which the stiffness may be constant during motion, but where it is important that one can switch to actuating the output stiffness immediately. However, it may be possible, when a mechanism is used that can split input power in a desired way, to output to the two degrees of freedom (e.g. 70% motion, 30% stiffness).

Although the proof of concept has been validated, further work needs to be done to characterize the system, and to examine the scalability of this system and prototype to certain (higher) output loads. Moreover, it should be investigated whether there is indeed a volume and mass decrease when compared to the common two motor designs.

VI. Conclusion

This paper has presented a novel variable stiffness actuator using only one (high power) input motor. The Single Motor–VSA (SM–VSA) is able to actuate position and stiffness

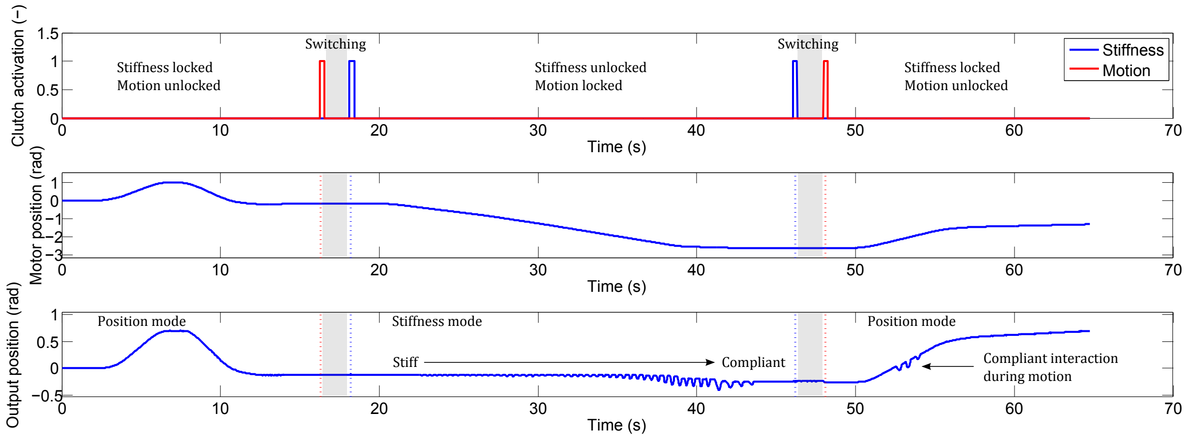


Fig. 11: Experimental validation of the concept. Clutch activation refers to the state of the motion and stiffness bistable mechanisms: a high signal means that the solenoid is powered, causing the locking or unlocking of the switch. First the motion degree of freedom is unlocked and actuated, after which at 16 seconds, the operational mode is switched to stiffness actuation. In this experiment the switching was done slowly (the grey shaded area is approximately 2 seconds wide), which was done to clearly indicate the switching sequence. The stiffness actuation mode starts in the stiffest setting and gradually goes to the most compliant setting, while the output is continuously disturbed (by manually tapping). At 46 seconds, the operational mode is switched again to actuate the motion, during which interaction with the compliant output occurs.

by locking and unlocking a degree of freedom in the VSA (either position or stiffness). This is done by bistable friction belt mechanisms, in which the diameter of a circular shaped flexure (the friction belt) is enlarged in diameter, causing it to engage to a surrounding cylinder, which generates friction and, thereby, locks a degree of freedom. The bistable mechanism ensures that the solenoids, that are used for the enlargement of the friction belts, can be very briefly powered, such that no electric energy is wasted in keeping a certain degree of freedom locked or unlocked. A prototype of the system was presented and an experiment was performed, which validates the novel concept.

VII. Acknowledgments

Éamon Barrett and Gerben te Riet o/g Scholten are acknowledged for their work and effort in preparing the prototype which allowed the validation of the concept.

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