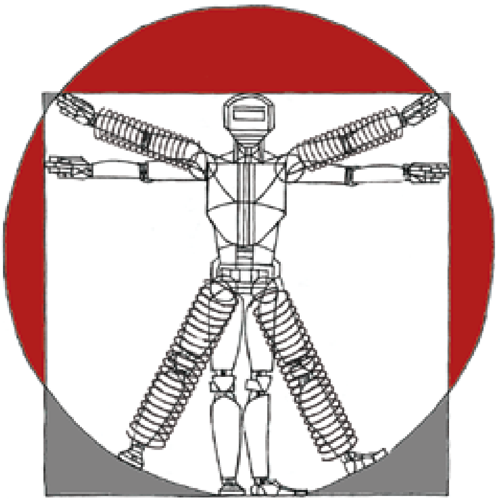
Towards a new generation of robots

The concept of variable stiffness actuators is of relevance to emerging robotics applications. In particular, the intrinsic compliance of the actuator can ensure safe human-robot and robot-environment interaction, even in unexpected collisions. From the analysis of two elementary design classes, lying at the basis of the majority of variable stiffness actuator designs, it is concluded that they are not energy efficient in changing the apparent output stiffness. This can be an issue in mobile applications, where the available energy is limited. Therefore, a new class of energy-efficient variable stiffness actuators is introduced. The conceptual design has been validated by means of simulations and experiments with a prototype realisation.



VIACTORS

• ***Ludo C. Visser, Raffaella Carloni and Stefano Stramigioli*** •

The advancements in robotics have caused major revolutions in the industrial world. In fact, thanks to robots, repetitive manufacturing processes can be performed endlessly with high repeatability and precision. This has resulted in lower costs and high quality of products. In order to achieve the required precision, the robots are mechanically stiff and are actuated by high-gain controllers, resulting in accurate motion. Moreover, to increase productivity, the robots are generally moving fast. The combination of high-speed motion with stiff actuation makes these systems potentially very dangerous, which explains why they are operating in environments where humans are not allowed.

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Compliant behaviour

In new emerging robotics applications, such as prosthetics, rehabilitation devices, and service robotics, human-robot and robot-environment interactions are an integral part. In such applications, the robotic system should show a compliant behaviour to prevent instability, damage or injuries. This approach is very similar to how humans perform tasks in unstructured environments: by pretension of the muscles, humans vary the stiffness of their joints to a specific level, appropriate for the task and the environment.

In robots, the compliant behaviour can be achieved by proper control action [6], but to guarantee intrinsic safety, a mechanical compliance should be introduced into the joints of the system. Ideally, the compliance should be variable, so to adapt it to the requirements of the task, and thus a trade-off between precision of motion and limited impact/interaction forces has to be found. For example, when moving slowly, the stiffness can be increased to achieve more accurate motion and it should be lower when the robot is moving fast, to ensure safe interaction in the case of a collision.

The requirement of mechanically variable stiffness joints is fulfilled by a new generation of actuators, called variable stiffness actuators [1], [2]. This class of actuators is characterised by the property that their apparent output stiffness, and thus the apparent stiffness of the joint they are connected to, can be controlled independently of the actuator output position, and thus the joint position. This can be achieved in many ways.
For example, the 'Jack Spring'™ achieves a variable stiffness by changing the number of active coils in a spring in series with the actuator output [4]. The actuator presented in [3] uses a variable configuration of permanent magnets to emulate a variable stiffness at the actuator output. However, most variable stiffness actuator designs present a number of internal elastic elements, usually springs, and some internally actuated degrees of freedom. The intrinsic properties of the elastic elements and the configuration of the internal degrees of freedom define the apparent output stiffness [5], [8], [12], [13].

In this article, some commonly encountered working principles for variable stiffness actuators are presented, and particular advantages and disadvantages of the principles are highlighted. In particular, it is shown how to design energy-efficient variable stiffness actuators, in which the internal elastic elements can be used for storage of potential energy, reducing the required control energy. Energy efficiency is especially an advantage in the actuation of mobile systems, in which the available energy supply is limited, e.g., walking systems or prosthetics.

Variable stiffness actuator designs

In this section, some variable stiffness actuator designs are presented. The discussion is restricted to the class of actuators that internally have a number of elastic elements and a number of internal degrees of freedom that can be actuated. In particular, two elementary design classes are considered, which encompass the majority of variable stiffness actuator designs presented in the literature.

To focus on the working principle, the following assumptions are made:

- the elastic elements can be represented by ideal springs, either linear or nonlinear;
- the internal degrees of freedom are purely kinematic, i.e., they have no mass or internal friction;
- other internal inertias and friction of the actuator can be neglected.

Moreover, it is assumed that the state s of the springs, i.e. their elongation or compression, is completely determined by the configuration of the internal degrees of freedom, denoted by q, and by the output position r. Formally, this means that there exists a map $\lambda : (q,r) \mapsto s$ such that $s = \lambda(q,r)$. The energy stored in the springs is a function of the state of the spring, i.e., $H(s)$, and thus either by changing the configuration q or the output position r, the energy stored in the springs can be changed. In particular, it follows:

$$\begin{aligned} \frac{\mathrm{d}H}{\mathrm{d}t} &= \frac{\partial H}{\partial s}\frac{\mathrm{d}s}{\mathrm{d}t} \\ &= \frac{\partial H}{\partial s}\left(\frac{\partial \lambda}{\partial q}\frac{\mathrm{d}q}{\mathrm{d}t} + \frac{\partial \lambda}{\partial r}\frac{\mathrm{d}r}{\mathrm{d}t}\right) \end{aligned} \tag{1}$$

This relation is used to investigate how efficient a particular actuator design is in terms of energy consumption in changing the apparent output stiffness, which is defined as:

$$K := \frac{\delta F}{\delta r} \tag{2}$$

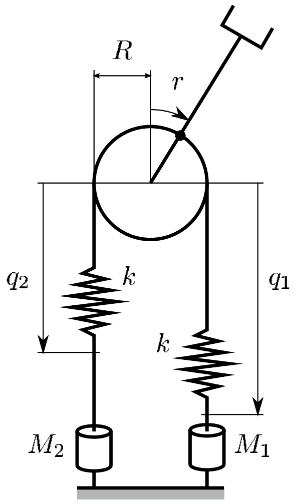

Figure 1. Design I - Variable stiffness actuator based on an antagonistic spring setup.

i.e., the infinitesimal change in the force F felt at the output, due to an infinitesimal change of output position r.

In this article, an intuitive analysis and discussion of the designs is presented. For a thorough mathematical treatment, the reader is referred to [9], [11], [12].

Design I - Antagonistic spring setup

The first design, schematically shown in Figure 1, is biologically inspired. Similar to the human muscular system, the design employs two springs in an antagonistic setup. The springs are nonlinear, to enable the independent control of output position and stiffness. Intuitively, by actuating the motors M_1 and M_2 in common mode, the pretension of the spring is increased and, therefore, the output is kept fixed but it becomes stiffer. While moving the motors in differential mode, the output position is changed. An example of an actuator of this type is the VSA [7], [8].

In this design, the springs are quadratic and, therefore, the force they exert is quadratic in the state, i.e., $f = ks^2$, with k the elastic constant of the springs. By investigation, it follows that the states of the two nonlinear springs are, respectively:

$$s_1 = q_1 - Rr, \quad s_2 = q_2 + Rr \tag{3}$$

The force F at the output is then derived:

$$\begin{aligned} F &= f_1 - f_2 \\ &= R\left(ks_1^2\right) - R\left(ks_2^2\right) \\ &= Rk\left(q_1 - Rr\right)^2 - Rk\left(q_2 + Rr\right)^2 \\ &= kR\left(q_1^2 - q_2^2 - 2R\left(q_1 + q_2\right)r\right) \end{aligned} \tag{4}$$

Using the definition (2), from (4), the apparent output stiffness K is given by:

$$K = 2kR^2\left(q_1 + q_2\right)$$

Observe that by changing q_1 and q_2 in common mode, i.e., $\dot{q}_1 = \dot{q}_2$, the stiffness is changed. In differential mode, i.e., $\dot{q}_1 = -\dot{q}_2$, the stiffness remains constant, while the output position changes.

The time derivative of (3) in matrix form is given by:

$$\begin{bmatrix} \dot{s}_1 \\ \dot{s}_2 \end{bmatrix} = \underbrace{\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}}_{A} \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \end{bmatrix} + \begin{bmatrix} -R \\ R \end{bmatrix} \dot{r}$$

The matrix A is a full-rank matrix, and, thus, regardless of the choice for $\dot{q}_1$ and $\dot{q}_2$, there is always a change of energy in the springs, i.e., using (1), $\dot{H} \neq 0$ for all $\dot{q} \neq 0$. In particular, when changing the stiffness, energy is put in the springs and internally stored, and therefore not usable for doing work on the load. Intuitively, by pretensioning the springs, the energy level in the springs increases, but since both springs are equally elongated, the forces on the output balance and hence the output position do not change. Therefore, this design is not energy efficient in the change of its apparent output stiffness.

Design II - Decoupled stiffness and position change

In the previous design, the springs have to be pretensioned simultaneously to change the stiffness, while a differential motion of the internal degrees of freedom leads to a change

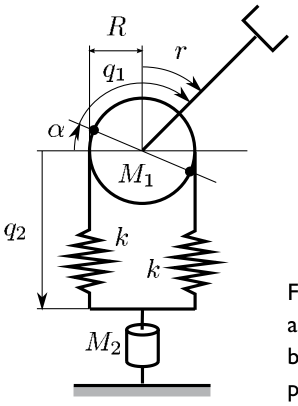

Figure 2. Design II - Variable stiffness actuator with complete decoupling between the change of the output position and the output stiffness.

of the output position. This observation has led to designs in which these two operations are decoupled and controlled by separate actuators. The design is schematically depicted in Figure 2. The linear motor M_2 changes the degree of freedom q_2, which realises a change of stiffness, while the rotational degree of freedom q_1, actuated by the rotational motor M_1, changes the output of the actuator with respect to the equilibrium position of the pulley. The VS-Joint [13] is an example of this type of design.

The analysis of this design is nearly identical to that of the previous design. Let the springs be quadratic, and by investigation of the kinematics, it follows that:

$$s_1 = q_2 - R\alpha, \quad s_2 = q_2 + R\alpha \tag{5}$$

with $\alpha = r - q_1 + \frac{\pi}{2}$. The output force is:

$$\begin{aligned} F &= f_1 - f_2 \\ &= R\left(ks_1^2\right) - R\left(ks_2^2\right) \\ &= Rk\left(q_2 - R\alpha\right)^2 - Rk\left(q_2 + R\alpha\right)^2 \\ &= -4kR^2\alpha\, q_2 \end{aligned} \tag{6}$$

Using the definition (2), from (6), the apparent output stiffness K is given by:

$$K = 4kR^2 q_2$$

which confirms that the change of the stiffness only depends on the degree of freedom q_2 and, therefore, is decoupled from the control of the output position, which depends on the degree of freedom q_1.

By differentiating (5) to time, it follows:

$$\begin{bmatrix} \dot{s}_1 \\ \dot{s}_2 \end{bmatrix} = \underbrace{\begin{bmatrix} R & 1 \\ -R & 1 \end{bmatrix}}_{A} \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \end{bmatrix} + \begin{bmatrix} -R \\ R \end{bmatrix} \dot{r}$$

Observe that the matrix A is full rank, and thus that, in order to increase the apparent output stiffness, energy has to be stored in the springs, i.e., $\dot{H} \neq 0$ for all $\dot{q} \neq 0$.

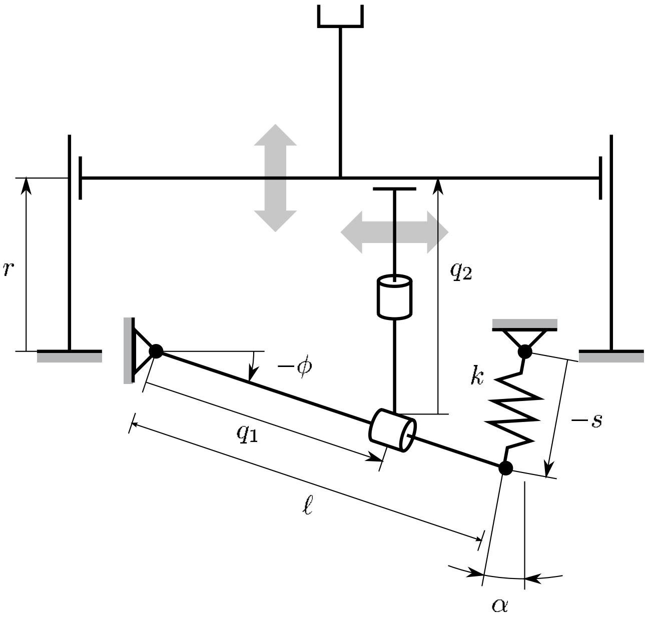

Figure 3. Conceptual drawing of vsaUT, a new energy-efficient variable stiffness actuator design.

Intuitively, in this design, increasing q_2 indeed increases the energy level in the springs, but the output position does not change. Therefore, this design is not energy efficient in the change of the apparent output stiffness.

A novel energy-efficient design

The observations made in analysing the previous two designs, regarding inefficient use of energy in changing the stiffness, gave the motivation to derive a new energy-efficient concept. In particular, the concept is such that the kinematics allows a change of stiffness without any change in the energy stored in the springs.

The concept, named vsaUT, is shown in Figure 3, and is extensively described in [12]. The working principle is based on a linear zero-free-length spring, connected to the output via a lever arm of variable length. How the spring is sensed at the output depends on the transmission ratio implemented by the lever arm. The effective length of the lever arm, and thus of the output stiffness, is determined by the linear degree of freedom q_1, while the linear degree of freedom q_2 controls the output position. Also AwAS [5] is based on this concept, but it realises a rotational implementation.

Assuming that the base length ℓ is large compared to the elongation of the spring, and thus $\alpha = 0$, from analysing the kinematics, the length of the spring is given by:

$$s = \ell \sin\phi = \ell \frac{r - q_2}{q_1} \tag{7}$$

Since the spring is linear, the force it exerts is given by $f = ks$. The lever arm introduces a transmission ratio $\frac{\ell}{q_1}$

between the spring and the output, and thus the force at the actuator output is given by:

$$\begin{aligned} F &= \frac{\ell}{q_1} f \\ &= \frac{\ell}{q_1} ks \\ &= \left(\frac{\ell}{q_1}\right)^2 k(r - q_2) \end{aligned} \tag{8}$$

Using the definition (2), from (8), the apparent output stiffness K is given by:

$$K = k\left(\frac{\ell}{q_1}\right)^2$$

and, therefore, the stiffness is uniquely determined by q_1.

Differentiating (7) with respect to time yields, in matrix form:

$$\dot{s} = \underbrace{-\frac{\ell}{q_1}\begin{bmatrix}\sin\phi & 1\end{bmatrix}}_{A}\begin{bmatrix}\dot{q}_1 \\ \dot{q}_2\end{bmatrix} + \frac{\ell}{q_1}\dot{r}$$

Observe that A is not a full-rank matrix, which implies that there exist $\dot{q} \neq 0$ such that $\dot{H} = 0$, i.e., the configuration q, and thus the apparent output stiffness, can be changed without changing the energy in the spring.

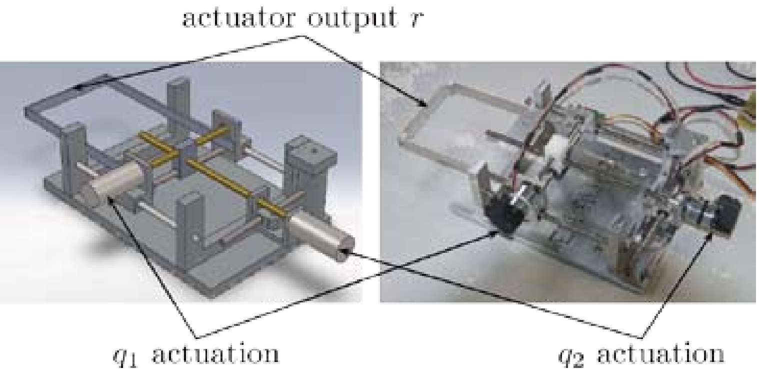

Figure 4. CAD drawing and photograph of the vsaUT prototype.

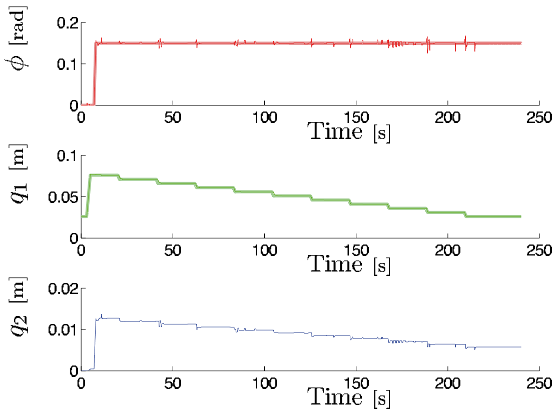

Figure 5. Experiment for determining the apparent output stiffness in the vsaUT prototype.

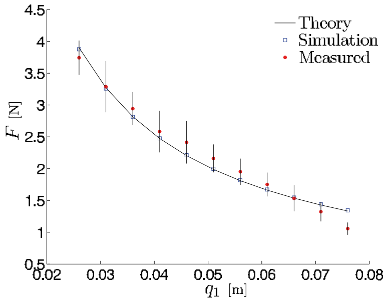

Figure 6. Evaluation of the apparent output stiffness by force measurements in the vsaUT prototype in theory, in simulations and in the experimental measurements.

Experimental validation

To validate that the concept indeed works as described in the theory, a simulation model and a prototype were built, as shown in Figure 4 and presented in [10].
The following experiment was conducted: the degree of freedom q_1 is preset to its maximum value, and the spring is preloaded by constraining the output motion r and by setting q_2 to some desired value. Using a force sensor, the force exerted at the output is measured, which is a direct measure of the stiffness, as follows from (2). Then, in equal steps, q_1 is moved to its minimum position, while q_2 is actuated such that $A\dot{q} = 0$, i.e., the spring length remains the same. At each step change of q_1, the force is measured. This experiment is shown in Figure 5, where the thick lines indicate the setpoint values. The above experiment was done both with the simulation model and the prototype.
The results are shown in Figure 6. The theoretical curve is described by $F = \gamma \cdot q_1^{-1} = 0.101 \cdot q_1^{-1}$, where γ is obtained from the design parameters. The experimental data can be accurately represented by the curve $F = 0.107 \cdot q_1^{-0.99}$, showing that the concept is indeed working as predicted by theory.

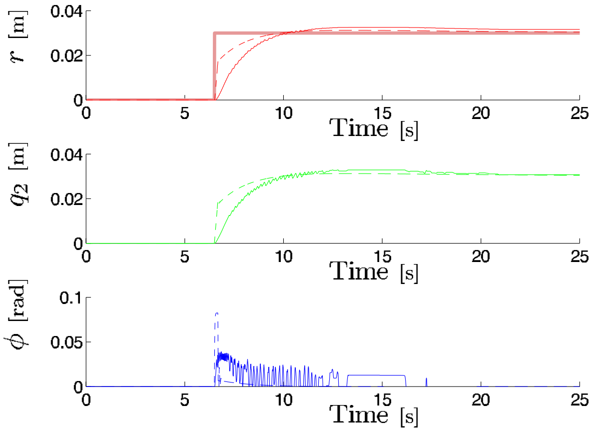

Figure 7. Actuation of a load with the vsaUT. Both simulation (dashed) and experimental (solid) results indicate that no energy is internally stored in the actuator.

A second experiment, presented in Figure 7, shows that in this concept no energy is stored in the spring that cannot be used to do work at the output. In particular, a step setpoint (thick line) for the output position, connected to a load, has been used. Due to the inertial properties of the load, the spring is initially compressed, but all energy stored due to this effect is eventually used for actuation, since the spring is not loaded at the end of the experiment.

Conclusion

The concept of variable stiffness actuators and their relevance to new emerging robotics applications have been presented. In particular, the intrinsic compliance of the actuator ensures safe human-robot and robot-environment interaction, even in unexpected collisions.

Two elementary design classes were presented and analysed. The working principles of these designs lie at the basis of the majority of variable stiffness actuator designs, proposed in the literature. From the analysis, it has been concluded that these designs are not energy efficient in changing the apparent output stiffness, which can be an issue in mobile applications, where the available energy is limited.

Triggered by this observation, a new class of energy-efficient variable stiffness actuators has been introduced. The conceptual design has been validated by means of simulations and experiments with a prototype realisation. The results show that the concept works as predicted by theory, and thus will form a new category of energy-efficient actuator designs.

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