Variable Stiffness Actuators: Review on Design and Components

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***Abstract*—Variable Stiffness Actuators (VSA) are complex mechatronic devices, which are developed to build passively compliant, robust, and dexterous robots. Numerous different hardware designs have been developed in the past two decades to address various demands on their functionality. This review paper gives a guide to the design process from the analysis of the desired tasks identifying the relevant attributes and their influence on the selection of different components such as motors, sensors, and springs. The influence on the performance of different principles to generate the passive compliance and the variation of the stiffness are investigated. Furthermore, the design contradictions during the engineering process are explained in order to find the best suiting solution for the given purpose. With this in mind the topics of output power, potential energy capacity, stiffness range, efficiency, and accuracy are discussed. Finally the dependencies of control, models, sensor setup, and sensor quality are addressed.**

***Index Terms*—Soft Robotics, physical Human-Robot Interaction, Variable Impedance Actuators, Variable Stiffness Actuators**

I. INTRODUCTION

A smart way to use energy is the central aspect of many recent technological developments. The capability to store and release energy is the game-changing factor in these fields. This can be seen in cars like in the Formula 1 with KERS (Kinetic Energy Recovery System), or in road traffic cars and buses with recuperation in hybrid engines, where the braking energy can be reused in a subsequent acceleration. Another recent example is Oscar Pistorius with his carbon fiber spring leg prostheses participating in the sprint at the Olympic Games 2012. There was even a discussion before the Olympic Games 2008 and 2012, whether he has unfair advantages over the able-bodied sprinters, and therefore should be excluded from the games. Also in robotic research energy buffering is a fast growing field of interest.

This paradigm change started with the publication of the work of N. Hogan on impedance [1] and of Pratt about the series elastic actuators (SEA) [2]. Their concept introduced an elastic element with constant stiffness between the gear and the actuator output. This concept has been subsequently augmented with the ability to deliberately vary the impedance. Currently, different principles exist to implement *variable* impedance in an actuator design. These robotic actuator units are called Variable Impedance Actuators (VIA) and its subgroup Variable Stiffness Actuators (VSA), which do not include dedicated damping elements. They are implemented in many different robot prototypes with a wide spectrum of intended applications. This includes entertainment robots, especially for children, to have a soft and huggable touch [3], [4] to gain better acceptance. Others focus on legs for walking, hopping, and running robots [5]–[10], and also active prostheses for a more natural and efficient walking [11]. Safety aspects, robustness, and dynamic performance improvements are the main motivation in robot hand and arm development, which enables applications like throwing or hammering [12]–[15]. In these systems joint stiffness can be changed mechanically in the VSA or by the controller [16]–[18] or in combination [19].

Recent research provides promising developments with different actuator principles, such as pneumatics [20], [21] or elastomeres [22]–[26]. This paper focuses on the electromechanical implementation of VSAs as the current state of the art promises to be advantageous in the combination of active bandwidth, output power, and positioning precision. In addition the majority of current developments of VSAs use electromechanical actuation.

Current robotic systems with compliant actuators have many different implementations with different principles. The variety and a typology of the field of VIA can be found in the accompanying review paper [27]. This rises two questions: Why are there so many developments, and is there a best solution/design, which fits all applications? Unfortunately, it can be said that there is no best solution, which deals best with all possible applications. But for a very specific task, it is possible to distinguish between better and worse performing principles and implementations. However, this rises the question of how to choose the best suiting layout from a bunch of possible solutions.

This paper gives insights of the design process of a VSA to find a good solution for the desired tasks. We present a reasoned strategy to approach the topic systematically from the analysis of the desired task to derived use-cases. These use-cases describe different kinds of basic motion components, which can be superimposed to gain the desired motion of the robot. The use-cases are analyzed to identify important physical aspects affecting the construction. Finally, we present how this knowledge can be used to gain a suitable actuator. The resulting list of specifications derived from the use-case analysis are combined in a data sheet that characterizes a VIA actuator (see section IV and the accompanying video). The specifications of the data sheets highlighted in this paper are mentioned in the text as *key attributes*. The data sheets form

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the connection to a different view on the topic - not from the designers point, but from the user's point. The user's point approach is presented in [28]. It provides a guide to choose one of the existing implementations to match the demands of the intended application.

II. USE-CASES FOR VIAS

Starting from the application of the future VSA articulated robot, the first step in building a VSA is the identification of basic use-cases. These use-cases are then prioritized, depending on their relevance to the intended application. These steps are very important in the design process as they directly affect the dimensioning of the VSA components. There are multiple use-cases to think of. The following list will only cover a subset, but in our opinion the most common ones.

- shock absorbing
- stiffness variation with constant load
- stiffness variation at constant position
- cyclic movements
- explosive movements

These use-cases will be discussed in detail in the following sections of the paper. At the end of each use-case a summary of the relevant key attributes of a VSA is given. These attributes will be discussed in more detail in section III-B.

A. Shock absorbing

One of the most important features of an actuator unit with intrinsic passive flexibility is the ability to resist fast and hard impacts without damage. Fast collisions between robots with a stiff structure and rigid objects with high inertia result in extremely short and high force peaks and large accelerations of the robot segment [29]–[31]. The collision forces on the actuator output can not be reduced by control even with a stiff, powerful, and agile robot like the DLR Lightweight Robot III [32]–[34]. Therefore, the actuator mechanics itself has to be able to withstand the impact and absorb, or buffer the influences of the impact. The difference between a common *rigid robot*, where the link is directly connected to the gearbox, and a robot with VIA, where the link is decoupled from the motor inertia by an adjustable spring/damper unit, can be seen in Fig. 1. The spring/damper unit helps to reduce the peak torque in the drive train between motor and link, and if it is flexible enough, it cushions the actuator from overload. VSA is a simplified version of a VIA with an adjustable spring unit, but without a mechanical damping unit.

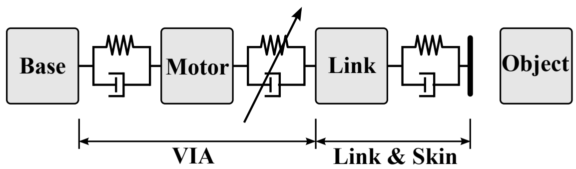

Fig. 1. Mass model of a 1-DoF variable impedance actuator (VIA) interacting with the environment.

When an object hits the robot link, the amount of energy or impulse affecting the robot is dependent of whether the impact is plastic or elastic. If the robot has a rigid structure, a plastic impact is caused by the damping characteristic of the robot skin and by inner deformations of the object. According to the type of impact the transmitted impulse of the impact and the resulting kinetic energy is calculated by the velocity and the link inertia with or without the additional mass of the object. This transmitted energy is buffered in the spring and, if applicable, also partially transformed to thermal energy in the damper. Here, the sum of the damping torque and the spring torque needs to be less than the fatigue limit of the drive train so that it is not damaged.

If the impact energy is larger than the energy which the spring/damper unit can buffer and absorb, the (torque) controller needs to react. This is done by moving the motor to match the velocity of the link after the impact, so that the passive deflection limit of the actuator is not exceeded. The passive deflection limit is the maximum position difference between motor and link that does not overload the spring. The deflection limit of VSA usually is in the range of several degrees. This dramatically increases the time in which a motor reaction is demanded. Compared to the relatively stiff torque controlled robots such as the previously mentioned DLR Lightweight Robot III, this lowers the requirements on the bandwidth of the motor and its controller.

Key attributes: *maximum elastic energy*, and *maximum deflection*

B. Stiffness variation at constant load

Changing the output stiffness is the core feature of a VSA. The stiffness variation can be separated into two basic interactions with the environment. One is changing stiffness at constant load and the second is changing stiffness at constant position.

Changing stiffness at constant load is very important for a flexible robot in tasks where a gentle force/torque interaction with the environment is desired. One example is a contour tracking task, where the endeffector of the robot arm is sliding on a surface and is intended to apply a certain amount of force. Depending on the surface structure and friction different stiffness setups will minimize the force/torque error. A bumpy surface for example will be tracked best with a soft setup, because tracking errors, which will naturally occur, will result in a lower deviation of the contact force. On the other hand surfaces or more precisely friction pairs with the tendency of stick-slip friction will be tracked better with a stiff setup to prevent the system from entering the stick phase.

Key attributes: *maximum stiffness*, *minimum stiffness*, and *stiffness variation time*

C. Stiffness variation at constant position

When the robot is changing stiffness at constant position, usually the robot is at a certain position or on a given track and the intention is that the stiffness should be modified without affecting the output position. This is analogous to humans co-contraction. So the goal is to maintain a low position error. As an example, when a robot arm holds an object in free space at a given position and external disturbances affect the object, the robot would stiffen up to reduce the position deviation.

On the other hand, when the disturbances affect the robot base, then the robot would be set to a soft setup. Therefore position disturbances will result in lower disturbing forces on the object. In addition the system has a lower eigenfrequency and so the controller has more time to react to the disturbance.

Key attributes: *stiffness vs. torque diagram*, *maximum stiffness*, and *minimum stiffness*

D. Cyclic movements

Cyclic movements consist of repetitive accelerations and decelerations of the robot. Here a robot with flexible joints can take advantage of the possibility to store potential energy in the VSA springs. As depicted in Fig. 1 a VSA can be modeled as a two mass system. The link mass can be excited by the motor to oscillate. This movement consists of repetitive acceleration and deceleration phases of the link. In the deceleration phase of the trajectory the kinetic energy of the robot link is transformed into potential energy of the spring. At the point, when the link is at its maximum amplitude all kinetic energy of the link mass is transformed into potential energy of the spring. This potential energy is released during the subsequent acceleration phase and converted to kinetic energy in the link. The frequency of this resulting cyclic movement is dominated by the eigenfrequency of the system and can be affected by a change of the stiffness setup or a change of the inertia, e.g., by a different pose of the robot [35], [36]. The amplitude can be modified to be larger or smaller by a superimposed movement of the actuator positioning motor(s). Please note that VSA with nonlinear spring characteristic do not have a eigenfrequency, but oscillate in ‘local eigenfrequencies’, which are amplitude dependent. The main advantage of VSA operating in cyclic movements is that the actuator positioning motors have to perform a much smaller movement than the desired output trajectory, which has the potential of saving a significant amount of energy. In a perfectly matching trajectory only the friction and damping in the VSA mechanism has to be compensated by the motor(s). There are few applications, where exactly the natural resonant trajectory is desired, e.g., a pure sinusoidal oscillation, with constant amplitude and frequency. Walking or jumping are examples for this. However such motions are present in cyclic movements and can be adapted to the desired output trajectories by a superposition of driving motor movements. So the trajectory can be influenced by control and also only parts of a cycle can be used in a trajectory.

Key attributes: *maximum deflection*, *maximum stiffness*, *minimum stiffness*, and *maximum torque hysteresis*

E. Explosive movements

Explosive movements are usually characterized by a high output velocity gained in a short period of time, which requires a high acceleration of the output.

Addressing the issue of the output peak velocity, VSA have the potential to accelerate the actuator output to a significantly higher velocity than the maximum velocity of the drive motor(s). To achieve this, one way is to somehow block the actuator output and apply a torque from the motor(s) to preload the springs. Afterwards abruptly releasing the output, the link will then flick over the equilibrium position like in a catapult, or when flicking a finger [37]. Another way is to use the strategy described in the cyclic movements (see Sec. II-D), but usually only one half-cycle with an additional acceleration of the actuator positioning motor(s) is performed. The resulting trajectory is a wind-up movement before reaching the maximum velocity [13], [38]–[40]. For the peak velocity task the energy storage capability is a dominating factor. The performance can be improved by starting the trajectory with a soft stiffness setup and stiffening it during the acceleration phase [38].

The maximum output velocity, which can be theoretically achieved is limited to the sum of:

- maximum velocity of the joint positioning motor(s)
- velocity gain by unloading the maximum potential energy of the spring

The latter case considers the transformation of the potential energy of the spring into kinetic energy of the output. The amount of velocity gain is inversely influenced by the output inertia. In addition the motor torque has to be big enough to load the spring completely, otherwise the energy capacity of the spring can not be fully used to accelerate the link.

One can say that changing the gear ratio of the actuator positioning motor(s) can also increase the output velocity, but this is always at the costs of maximum output torque. The nice thing about using the intrinsic flexibility is, that you can have both: a high static output torque and high, even though short, output velocity.

In a VSA only the motor torque or postion can be controlled directly, so the controlled state and the output position are non-collocated. Assuming the motor and link inertia can not be influenced significantly, the execution time of an explosive movement is influenced by the maximum motor torque and the spring stiffness of the VSA. At first, the bigger the motor torque is, the faster the motor inertia can be accelerated. Second, the higher the spring stiffness is, the faster is increase in the spring force for the same passive deflections, which accelerates the actuator output. In other words, the active bandwidth is increased by the higher motor torque and higher stiffness.

Key attributes: *peak torque*, *maximum speed*, *maximum elastic energy*, and *stiffness variation time*

III. Design of a VIA device

A. Design concepts

The numerous VSA principles developed since the late 80s are too diverse to cover in this paper. The overview paper [27] is addressing the whole set of possibilities to create a VSA device. Here we want to point out the main factors influencing the most common design approaches, which affect the system performance and behavior.

1) Motor setup: One of the most important choices to make is whether to use an antagonistic system with two opposing motors like in the human archetype (see Fig. 2a), or a system with independent motors for joint positioning and stiffness variation (see Fig. 2b). There are also setups similar to the independent motor setup with a coupling between the motors and the output and stiffness setup respectively, e.g., the quasi antagonistic principle [31], [41], but here most of the benefits and drawbacks are the same as for the pure independent motor system. So we will focus on the two main setups:

- antagonistic motor setup
- independent motor setup

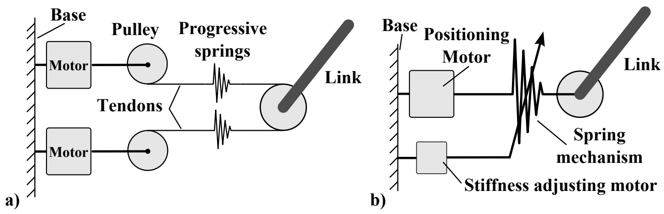

Fig. 2. Different VSA principles with a) antagonistic and b) independent motor setup.

In an antagonistic system a movement of the motors in the same direction results in an output movement and co-contraction of the springs by moving both motors in opposite direction results in a change of output stiffness. Both motors and springs oppose each other and have in most cases the same size. The positive effects of this setup are that the power of both motors contributes to stiffen the actuator and for tendon driven systems a change of length between the actuator and the joint can be easily compensated. The latter is important, e.g., for robotic hands where the actuators are located in the forearm and the tendons run through the wrist to the finger joints. One drawback is that unless the antagonistic VSA is bidirectional [42]–[44] the maximum output power and torque of only one of the motors and also the energy storage of only one spring can be used. Another point is that for moving the output both motors and potentially gearboxes have to move and as a result the power losses of all four elements show up. These losses are increased for a stiff setup, because then the sum of the load in the drive-trains is larger than the output torque. The above mentioned bidirectional antagonistic system has a unique ability compared to the other setups. It can move the output, even if one of the driving motors/electronics is faulty, but is still backdrivable.

A setup with independent motors only moves one motor to vary the output position and has as a result only the losses of one motor and if applicable one gear. Additionally this setup contains the possibility to use only one spring in contrast to the antagonistic setup where two springs are needed to be able to change the stiffness by co-contraction. The stiffness setup of the actuator with independent motors is changed by a dedicated motor. So the size of the stiffness adjusting motor can be chosen to match exactly the power needed for this purpose, which usually results in a much smaller stiffness adjuster than the main positioning motor. This design promises to gain smaller and lighter actuators. A drawback of this approach is, that only the power of the positioning motor can be used to move the joint and thus this defines the output power of the actuator and also for changing the stiffness setup only the power of the stiffness adjuster can be used.

2) Stiffness variation: There are three methods to change the stiffness of a VSA. All of them can be used in combination with an independent or antagonistic motor setup.

- variation of the spring preload
- variation of the transmission ratio between output and spring
- influencing the physical properties of the spring

Further details on the possible physical implementations of the three methods are presented in [27]. In the following paragraphs the influence of the three methods on the system attributes are discussed.

Changing the spring preload is potentially the simplest way to change the stiffness preset. In most existing VSA based on this effect it was realized by only a few simple mechanical components, e.g., [45]. A classical antagonistic system is changing its stiffness by co-contraction, which results in a preload of the springs. Please note that for an antagonistic system the springs have to be non-linear progressive to achieve a stiffening effect, e.g., springs with a quadratic spring function for a linear output spring function [46], [47]. The most important drawback of the spring preload method is that the potential energy stored in the spring by compression/extension can not be used to store energy from the VSA output anymore until the pretension is released again. So this method directly decreases a key feature of a VSA by reducing the potential energy capacity at stiff actuator setups (see Fig. 3) [38], [48]–[50].

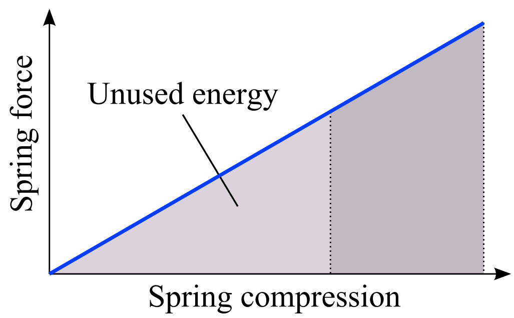

Fig. 3. If the stiffness adaption of the VSA is realized by a spring preload instead of a change of transmission ratio, the energy capacity is reduced for higher stiffness presets. The pretension increases the spring force at the same passive deflection and so results in a stiffer setup. The energy used to compress the spring (lighter shaded area below the line) cannot be used for the passive deflection anymore. The examples is for a linear spring, but holds also for a progressive spring, which is usually used in pairs in an antagonistic setup.

Changing the transmission ratio between the actuator output and the spring element directly affects the displacement of the spring caused by a passive movement of the output, e.g., [51], [52]. As a consequence this method directly affects the spring rate of the actuator output and the potential energy storage is not reduced by changing the stiffness setup. Hence, in a stiff setup the passive deflection range is less reduced than in a spring preload type actuator. The drawback of mechanisms which are able to change the transmission ratio is that they are usually more complex than spring preload types, which results in more moving parts and is potentially less efficient.

Adjustable physical spring properties are a way to change stiffness, and this is a field of interest of many research groups world wide. Besides others polymer and nano material scientists are working on this topic, but there are also mechanisms with, e.g., steel springs which change the active length of the spring to change the stiffness, e.g., [53], [54]. At present mechanisms using spring preload or a variation of transmission ratio have a higher energy capacity than the previously discussed techniques relative to the size and weight.

B. Design contradictions

In the design phase of a VSA or almost any other mobile electro-mechanical device there is a clear and obvious conflict between the size and weight of the system. Eventually, there is an additional restriction on the costs of the desired system.

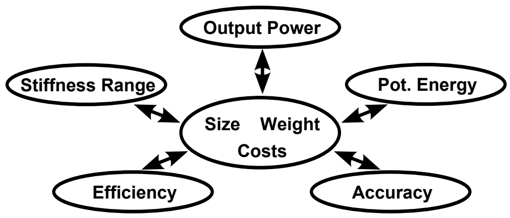

Fig. 4. Design contradictions of the different actuator attributes during the design phase of a VSA.

This group of the three factors of size, weight, and costs is in conflict with five other attributes that describe a VSA (see Fig. 4), i.e., output power, potential energy storage, stiffness range, efficiency and accuracy. All six groups are described in the following.

1) Size, weight, and costs: VSA are usually intended to be used in robotic arms and legs, where the possible size and weight are very limited. The units have to be very compact to fit in such a system, especially if it is intended to be a mobile system like a humanoid of adult or even smaller size. The weight of the VSA units is a dominant factor in these systems. So the weight of the VSA directly affects the system performance, because it statically reduces the payload in an environment with gravity, and increases the inertia of the links, which reduces the active and passive bandwidth of the system.

Compared to a common rigid robotic actuator a VSA is a much more complex system. To be able to change the stiffness each actuator has to consist of at least 2 motor units, usually with 2 corresponding gears, and a spring mechanism (see [55]). A rigid robotic joint has typically only one motor unit, one gear, and eventually a torque sensor. In VSA with no passive damping, usually the torque sensor can be omitted by using a good model of the spring characteristic. Nevertheless a robotic joint equipped with a VSA is more expensive than a common robotic joint. The costs of a high performance commercial robot with VSA built in, are likely to be more. Depending on the budget the VSA has to be composed of cheaper and in most cases inferior parts. This will limit the capabilities of the whole robot.

2) Output power: The spring of a VSA can provide a short time extra power boost, if it is pre-loaded. However, the output power of the VSA, which can be provided continuously and reliably is specified by the power capabilities of the motor(s).

The continuous output power of the VSA is the power, which the actuator is able to provide without stopping. It is the nominal speed multiplied by the nominal torque of the positioning motor(s) (see Fig. 5). Nominal speed and torque of the motors can be found in the motor data sheets. An electric motor can generate a higher torque than the nominal torque by applying a higher than the nominal current, but this is limited in time and will be shorter for higher currents. Otherwise the windings will be damaged by overheating. So the maximum torque of the electric motors can be a multiple of the nominal torque for a short period of time. This can be very interesting for short, highly-dynamic applications, such as the high peak velocity use-case (see Sec. II-E). In this instance there is also the benefit that, at less load than the nominal torque, the achievable velocity is higher than the nominal velocity. The maximum speed, without operating in generator mode, can be achieved at zero external load. How big this velocity gain is depends on the motor and power electronics setup. A good way to present the capabilities of the driving unit is the torque-velocity diagram with the continuous and short time operation areas. This diagram is also used to describe the VSA output performance, which then includes all transmission ratios between the motors and the actuator output. An extension to the described two-dimensional diagram is to have the output stiffness as a third dimension, which gives a visual overview on the influences of the stiffness setup on the output power (not depicted, see data sheets on [56]).

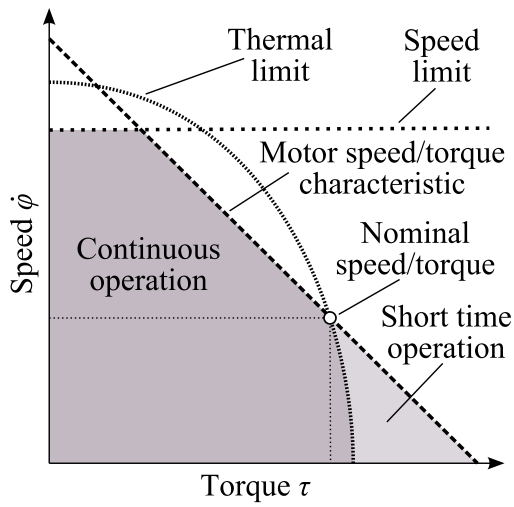

Fig. 5. The speed vs. torque diagram is directly connected to the motor characteristics, which define the thermal limit and speed/torque curve limit. The thermal limit may be exceeded for a short time without causing damage to the system. The speed limit is usually set by the bearings and gears of the system.

3) Potential energy: The maximum potential energy, which can be stored in the VSA, is determined by the integral spring(s). Assuming that the full energy of the active spring can be used by a passive actuator deflection, the maximum elastic energy of the VSA is the same as that of the active spring. As previously mentioned in Sec. III-A2 the usable elastic energy may be reduced by a change of the stiffness setup. Additionally in an antagonistic setup (see Sec. III-A1) only one of the springs is, depending on the load direction, the active spring, which is storing the elastic energy.

The elastic energy stored in the VSA is

$$H(\varphi, \sigma) = \int_0^{\varphi} \tau(\varphi, \sigma)\, d\varphi \tag{1}$$

with the external torque $\tau(\varphi,\sigma)$, the passive deflection φ, and the stiffness setup σ. As described before $H(\varphi,\sigma)$ is limited to the potential energy capacity of the active spring. Having a look at the external torque-deflection diagram (see Fig. 6) the elastic energy stored in the actuator is the area below the torque curve. Basically the VSA mechanism forms a transmission between the output and the spring, which can be altered by a change in the stiffness setup. So the available energy can be distributed over the torque-deflection curve and if the general characteristic of the torque function is maintained, an inverse relationship of maximal deflection and maximum torque is obtained. Increasing the maximal deflection will result in a decrease in the maximum torque and vice versa. A way to enlarge the maximum torque *and* deflection is to modify the torque function in a way that it is non-linear progressive with a low slope at low deflections and a high slope for high deflections, so that the integral has the same value as the one of the previous torque function (curve d). With output stiffness $k(\varphi,\sigma)$ being the derivative of the torque function, a lower slope at low deflections has a lower stiffness in this region.

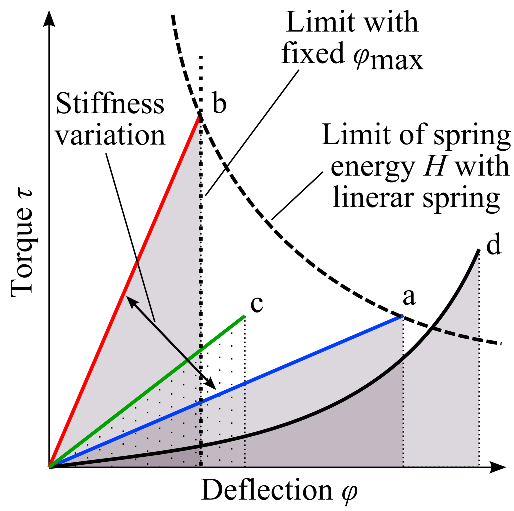

Fig. 6. A VSA-device, which changes the transmission ratio between spring and output, does not reduce the energy capacity in different stiffness setups (see curve a and b). The potential energy at maximum passive deflection shown by the area below the curves is the same. A stiff setup of a spring preload type VSA has less energy capacity (dotted area below curve c). A mechanical end stop at a fixed $\varphi_{\max}$ cuts off all curves at the given deflection. A progressive curve (d) with the same potential energy has a lower stiffness at small deflections and a maximum higher torque than the linear curve.

In the diagram the influences of the stiffness variation method on the elastic energy capacity can be seen (see also Sec. III-A2). A stiffer setup achieved by a variation of transmission ratio does not affect the elastic energy capacity, represented by the dashed line of

$$\tau_{\max}(\varphi) = \frac{2\,H}{\varphi} \tag{2}$$

with the energy capacity of the spring H. In contrast, a spring pretension (curve c) reduces the energy capacity, which can be seen in the dotted smaller area below the curve.

For constructive or practical reasons some VSA do not limit the maximum deflection according to the potential energy capacity of the spring, but have a limit on a fixed deflection $\varphi_{\max}$ realized as a mechanical end stop. This limit is usually chosen, so that the maximum torque can be realized with the maximum stiffness setup. With this limitation the most energy can be stored with the stiffest setup and the energy capacity for lower stiffness setups is decreased. This effect can be seen for curve a in Fig. 6, which would be cut off at $\varphi_{\max}$ in this case.

4) Stiffness range: The stiffness function $k(\varphi,\sigma)$ is defined as:

$$k(\varphi,\sigma) = \frac{d\tau(\varphi,\sigma)}{d\varphi} \tag{3}$$

Depending on the task, the possibility to have a broad stiffness band at different external loads may be beneficial. For stiffness variation and cyclic tasks (Sec. II-B - II-D) particularly the bandwidth of the actuator stiffness is important. A helpful tool to get an overview on the actuator stiffness performance is the stiffness-torque diagram (see Fig. 7, 8). Here the minimum and maximum stiffness and their inter-dependency with the external torque and the different actuator stiffness setups can be examined. It gives a distinct visualization of the stiffness bandwidth at a given loading case, which is the freedom of variation in vertical direction. The stiffness bandwidth is the most important factor for the performance in the 'stiffness variation at constant load' use-case (see II-B).

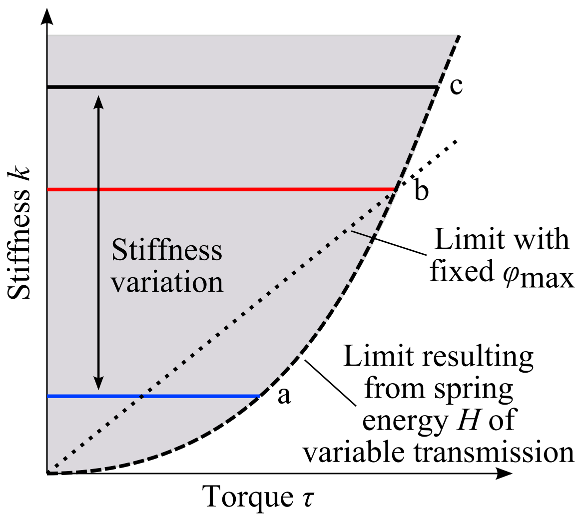

Fig. 7. Stiffness variation of an actuator with a linear torque-displacement characteristic at different stiffness setups. The dashed line is the maximum spring energy limit for a variable transmission type VSA. The dotted line gives the limit for a fixed deflection angle $\varphi_{\max}$.

Fig. 7 deals with a VSA with constant stiffness for different stiffness setups a-c. The constant stiffness makes it easy to model the actuator dynamics and the unaffected oscillations of the system can be expressed in eigenmodes. The limitation of the maximum deflection $\varphi_{\max}$ resulting from the energy capacity of the spring(s) has different characteristics depending on the stiffness variation principle used. There is a lower bound on the stiffness for the variable transmission type, which can be expressed as

$$k_{\min} = \frac{\tau^2}{2\,H} \tag{4}$$

For practical reasons it might be desirable to have a non-linear progressive actuator torque curve (see curve d in Fig. 6),

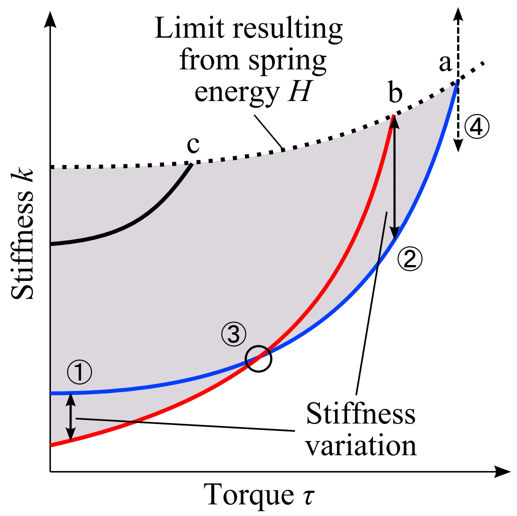

Fig. 8. The external torque-stiffness diagram of an actuator with a progressive torque-displacement behavior. Stiffness variation under a constant load corresponds to a vertical shift in the diagram. The dashed line is a potential limiting effect of reduced maximum deflection angle φ_{limit} set by pretension of the spring(s). In loading case ① setup a is stiffer than setup b, but in ② setup b is stiffer than setup a. This behavior may result in difficulties in the controller design. In loading case ③ an intersection of the stiffness setup curves makes it impossible to vary the stiffness between a and b. This drawback is emphasized, if all stiffness setups have an intersection at the same load case. In case ④ the stiffness can not be altered, because in other stiffness setups the passive joint deflection or maximum torque is exceeded.

which results in non constant torque-stiffness curves as shown in Fig. 8. The reason may be one of the following:

- gain a higher maximum torque and deflection than a linear torque curve with the same spring energy
- a stiffening effect helps the actuator to avoid reaching the mechanical end stops
- shaping of the end-effector stiffness of a kinematic chain according to a desired passive response

The latter point is of special interest in the field of hopping and walking robots, where a progressive knee actuator in a robotic leg facilitates a linear endpoint stiffness.

The time to change the stiffness setup is influenced by the stiffness variation principle. In a spring preload type where energy has to be stored in the spring(s) to increase stiffness, the motor(s) have to provide the relevant energy and depending on the motor power this takes more or less time. Similarly, for a variable transmission type the motor power influences the stiffness variation time, especially when the stiffness should be increased with an external load applied. This is even the case, if the mechanism was designed in a way that it does not need to emit power at the output whilst the stiffness is increased [57]. Here both motors have to resist at least the external load while moving in a way so that the equilibrium position at the actuator output keeps constant. In this case the motors have to overcome the inevitably friction losses, which will also limit the time of stiffness change. When the stiffness changing motor is chosen very small, it may be even the case that it is not able to set all desired stiffness setups when an external load is applied.

5) Efficiency: Energy is transformed between kinetic and potential energy repeatedly during the movement of a robot with VSA-articulated joints. Therefore it is essential that the energy can be transformed efficiently. That implies at first that we keep the friction in general as low as possible, so that we do not loose the energy unintentionally during operation. We have to avoid friction bearings, and reduce the overall number of bearings. Usually the friction in the actuator mechanism is much higher than the inner losses of the spring. For cyclic movements (Sec. II-D), where the oscillation is performed primarily without motor movements, the efficiency in the drive train between the robotic link and the spring(s) is relevant.

A good plot to investigate the efficiency of the VSA-mechanism is the torque-deflection graph with the torque measured by a external torque sensor at the output. This measurement can be performed for different stiffness setups and deflection velocities. The losses in the mechanism can be seen in the diagram as a hysteresis in the external torque at the output for the movements with increasing vs. decreasing deflection (see Fig. 9). The area contained within the loop represents the losses during one cycle. In most actuators the losses are higher for a higher stiffness, because then the load inside the mechanism and thus the friction is higher. This is especially the case for the spring preload type of VSA. If a model of the torque-deflection characteristic of the actuator exists, a second diagram can be plotted with the torque error, i.e., output torque minus the modeled torque versus the deflection. In this plot (see Fig. 10) the ideal frictionless actuator would have a horizontal line with the value 0. The torque hysteresis caused by the friction can be considered as a symmetric vertical deviation of the loading and unloading motion. Model errors primarily result in asymmetric vertical deviations.

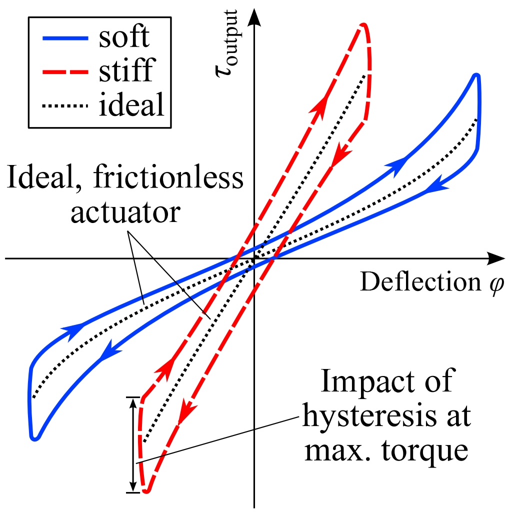

Fig. 9. Qualitative diagram of output torque vs. the passive deflection of the actuator. Friction causes a hysteresis in the direction of the measured torque which is usually higher for stiffer actuator presets. The dotted lines indicate the behavior of an ideal frictionless actuator with a nonlinear characteristic.

Efficient motors and gears that also feature high peak energy throughput are essential for the efficiency of the transformation of energy between the electrical and the mechanical domain [58], [59]. This is useful, e.g., for the peak velocity use-case, or tasks with large movements, or high output power. Since gears and motors are usually provided by suppliers, their efficiency can be looked up in the corresponding data sheets.

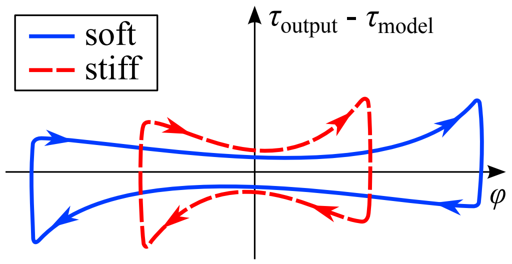

Fig. 10. Qualitative diagram of output torque hysteresis vs. the passive deflection φ of the actuator. This graph is a tool to investigate deviations of the real system from the model. Friction causes a symmetric hysteresis in the vertical direction. Model errors result in asymmetric vertical deviations.

With a dedicated stiffness adjusting motor, there is some potential to save some energy during operation. If the desired stiffness variation time is low, a small motor with a high transmission ratio can be used, which has in static operation less power consumption. If frequent stiffness variation during operations is not necessary, a non-back-drivable gear can be used for the stiffness adjusting motor. Then the motor does not have to apply a constant torque to maintain its position, so that it has no power consumption in the time where the stiffness setup is not changed. This is usually at the cost of a less efficiency, when the stiffness adjusting motor has to move.

6) Accuracy: Most people who are new to the field of VSA have intuitive concerns on the accuracy, repeatability, and predictability of the system. The good news for them is that VSA based robots can be precise and predictable, but like other robots their performance in accuracy is strongly dependent on the quality of models, machined parts, the sensors, and the design itself. In this section we want to address the sensors and the design.

It is obvious that the precision of the VSA is set by the build quality of the sensors. Thus high resolution sensors are obligatory for a precise VSA. Position sensor resolution is particularly important for velocity measurement. Velocity is the time derivative of the position signal, so errors as well as spacial and time discretization effects influence significantly the quality of velocity measurement. With a given sensor resolution q_{res} the corresponding velocity resolution $\dot{q}_{\text{res}}$ is

$$\dot{q}_{\text{res}} = \frac{2\pi}{n_{\text{inc}} * t_{\text{sample}}} = \frac{q_{\text{res}}}{t_{\text{sample}}} \tag{5}$$

with the sample time t_{sample} and the number of increments n_{inc}.

A 12 bit sensor in a realtime setup running at 1 kHz has a velocity resolution of

$$\dot{q}_{\text{res}} = \frac{2\pi}{2^{12} * 0.001}\frac{\text{rad}}{\text{s}} = 1,53\frac{\text{rad}}{\text{s}}. \tag{6}$$

Assuming 2 increments peak to peak noise, the unfiltered noise is 3.06 rad/s ($175\,°/s$), which is faster than the maximum joint velocities in typical pick and place movements of current humanoid robots. In this case a strong filter on the velocity signal with an undesired phase shift would be needed.

Furthermore sensor hysteresis and temperature drifts of the sensors, as well as time delays and limited bandwidth of the filters and the digitalization should be addressed in the selection of the position sensors.

The accuracy is influenced by the placement of the senor and which position is measured against which reference. Sensors arranged in series and values where model knowledge is necessary should be avoided as far as possible. As depicted in the example of Fig. 11, the link position can be measured directly or calculated as the sum of the motor position, spring length, and eventually a load dependent impedance model of the gear box and tendons. With an appropriate sensor, the direct measurement is more accurate than the calculated value, because in the latter case, the sensor and model errors, as well as the noise are summed. In the given example the peak to peak noise of two serial 12 bit sensors is 6.12 rad/s.

On the other hand the method of indirect measurement enables us to avoid placing sensors at unfavorable positions. In the example the sensors are placed around the moving springs and thus have to move with the springs during operation. As a consequence the sensors are exposed to high accelerations and vibrations, which may be harmful and have a negative effect on the measurement. On the other hand the spring length could be also obtained as the difference between the motor and spring position which could be both measured by sensors attached to the VSA-base.

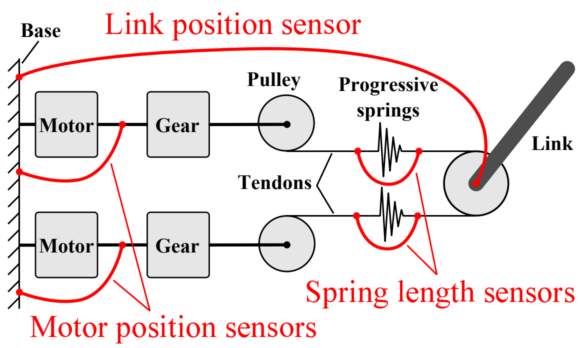

Fig. 11. Sensor positions for an antagonistic VSA. The sensor placement directly influences the quality of the measured data. Values can be measured directly or can be calculated as a sum of serial arranged sensors and eventually models. In the example the link position could be measured directly or calculated as the sum of motor position, spring length, and possibly a load dependent impedance model of the gear boxes and tendons.

With a well designed sensor setup the controller knows the state of the actuator, but for a precise and repeatable movement it is essential that the driving motor is able to affect the output position and torque. Any kind of backlash, play in the drive train, cable slack, creeping, or slip-stick friction may harm the accuracy of the output position and torque. Therefore these effects should be explicitly addressed and minimized in the mechanical design of the VSA.

C. Influences of the control on the design

The controller relies on the knowledge of states of the system. In contrast to rigid or constant stiffness actuators with 4 state space variables VSA have 6. These are the positions of the output and the 2 motors, plus their derivatives. Alternatively they could be substituted, e.g., stiffness adjusting motor position by actuator stiffness, or output position by output torque, plus their derivatives, respectively. Possible variables of the state-space of a VSA are listed in Table I. For

TABLE I
LIST OF POSSIBLE STATE-SPACE VARIABLES OF A VSA.

motor positions	θ	motor velocities	$\dot{\theta}$
output position	q	output velocity	$\dot{q}$
output stiffness	k	output stiffness derivative	$\dot{k}$
output torque	τ	output torque derivative	$\dot{\tau}$

a VIA with additional variable damping the damping factor plus its derivative is needed.

Some VSA states can not be measured directly, e.g., the stiffness can not be estimated without a change in the external load or an at least quasistatic model of the actuator [60]. Other states such as the torque can be measured using costly torque sensors, but most engineers decide to use a model to calculate the torque using cheaper position sensors to measure the passive deflection and the stiffness setup, e.g., co-contraction in the example of the antagonistic VSA of Fig. 11. Furthermore, position sensors tend to have less temperature drift and signal noise than strain gauge based torque sensors, which is crucial for the controller performance using the torque derivative. Extra information such as the temperature can be used for a sophisticated model of friction and damping or a calculation of the performance limits when overpowering the motors.

In the example shown in Fig. 11 the link position can be estimated by the motor and spring sensors and measured by a dedicated sensor. This redundancy can be used to close the measurement loop so that a deviation of the two values can be observed. This enables the controller to detect failure of sensors or the mechanics and helps ensure safety of the robotic system.

Modeling a system state has some direct issues in the accuracy of the state. Friction and play can be difficult to model exactly, resulting in a torque hysteresis, and with it limits on the performance of the controller. Also structure elasticity and creeping effects, e.g., in tendons, are challenging to model precisely because they are mostly nonlinear [61], [62]. In addition creeping is plastic effect dependent on the load history and temperature. All these effects are particularly difficult to handle when they appear at positions which can not be measured by a sensor, e.g., friction in the output bearing can not be measured by an integrated torque sensor or by spring deflection. Furthermore, in the example of the antagonistic actuator the torque and output position could be estimated by only measuring the motor positions and spring lengths, and leaving out the link side sensor. But tendon creeping and gear hysteresis can not be observed. They may be modeled, but can not be evaluated. So depending on the magnitude of these effects, the link position is at best a good guess.

In the case where the actuator is equipped with a damping unit to reduce unwanted oscillations of the output, usually a torque sensor is required. The reason is that dampers are extremely hard to be modeled precisely and as in the previous example of the position sensor placement, the model could not be evaluated without, in this case, a torque sensor. This is independent of the positioning of the damper, which is reasonably placed in parallel to the spring mechanism or directly between output and base. In addition, some damping systems like a controlled friction damper [63] rely on a correct output torque signal.

In general, using a model instead of directly measuring the state has advantages:

+ less parts
+ smaller
+ cheaper
+ lighter

But it may have drawbacks:

- less accurate
- needs better and more expensive additional sensors
- higher computational power
- errors are more likely not detected

IV. DERIVATION OF THE VSA DATA SHEETS

The investigations of the applications, use-cases, and design issues lead to the identification of the attributes and plots discussed in the preceding sections. All this information is very useful to describe a given VSA-device. If you want to get an impression of the performance of a VSA, discuss on the specific advantages and drawbacks, or investigate on the suitability for a desired task, you would need a subset or even all of this information of a VSA. Out of this large amount of information, which is most likely not transparent to the reader in the written form, we composed the VSA Data Sheet. In this data sheet we put in all the values of the attributes and graphs addressed before, and in addition the electrical and mechanical interfaces. All the data is grouped into several logical blocks to give a compact and clear set of information. The different sections include the main electrical and mechanical properties, details on the sensors, the spring characteristic, the mathematical description, and details of the internal actuator design. The single values and plots of the data sheets are presented in detail in the complementary paper [28].

The VSA Data Sheet was developed in the VIACTORS European project and is an attempt to provide a common interface for the world wide community working on the topic of VSA and it is open to all. The data sheets of the actuators developed by the groups within the project as well as the template for the data sheet can be downloaded at `www.viactors.org`.

V. CONCLUSIONS

Starting with the intended purpose of the robot different use-cases are identified, which resemble characteristic types of basic motions. The separate use-cases are investigated and the most relevant physical parameters and design parameters are derived. Like in most engineering work, many of these parameters are in conflict with each other and can not be chosen arbitrarily. The parameters are grouped into five different functional categories and their influence on the design is discussed. Additionally, the influence of the controller is shown. The VSA Data Sheets are invented and consist of the most relevant data describing a given VSA-device. The data sheets are invented to from a connection between researchers coming from the users point of view on VSA and researchers involved in the VSA design.

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