2013 IEEE/RSJ International Conference on
Intelligent Robots and Systems (IROS)
November 3-7, 2013. Tokyo, Japan

Towards a Robust Variable Stiffness Actuator

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Abstract— **Robots with Variable Stiffness Actuators (VSA) are intrinsically flexible in the joints. The built-in mechanical spring not only has the advantage of a higher peak performance, but also leads to a more robust robot. This paper presents and analyzes the threats to a VSA equipped robot that arise from external or internal origin. Influences of mechanical, moisture, electrical, thermal, radiation, and chemical nature are identified. Protection methods from these threats are discussed and the results presented. The results are separated into hardware, observation, control limiters, and reaction strategies. A hierarchical implementation of the control limiters and reaction strategies is presented. The reaction strategies use a motor position deviation and a change in the stiffness setup to reduce the load at high passive deflections in the VSA. Control limiter and reaction strategies have been implemented in the DLR Hand Arm System and evaluated experimentally with impacts on the system.**

I. INTRODUCTION

Variable Stiffness Actuators (VSA) are intrinsically compliant robotic actuators, that are able to actively change position and stiffness of the output. They extend the idea of the well known Series Elastic Actuators (SEA) [1], which feature constant stiffness. Both concepts are based on a passive elasticity deliberately built-in the drive train between actuator motor and actuator output. The field of VSAs has been rapidly growing over the last years (see [2]). It is especially addressed by researchers interested in robot manipulator arms and humanoids operating in close range or even direct physical contact to humans. But why would anyone want to sacrifice active output positioning bandwidth by using the lower stiffness in the drive train? Basically the VSA concept promises three different benefits:

- Potential energy can be stored in the elasticity of the actuator. This exploited energy can be used to extend the peak performance.
- In some situations the safety to humans interacting in direct contact is improved, e.g., in clamping situations.
- The robustness of the robot itself can be enhanced.

Besides of the short-time peak performance, there are functional extensions where shock absorbtion is part of the task. Previous work has shown that robotic prototypes equipped with VSAs are extremely robust to accelerations or decelerations of the output by external forces. Practical examples are, e.g., actively hopping [3], kicking a soccer ball [4], playing drums [5], or passively being hit by a falling weight [6], a hammer [7], or a baseball bat [8].

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This work has been partially funded by the European Commission's Seventh Framework Programme as part of the VIACTORS project (grant number 231554*) and the SAPHARI project (grant number* 287513*)*

Fig. 1: DLR Hand Arm System using a hammer.

The main focus of this paper is the robustness of a robot equipped with Variable Stiffness Actuators. A more robust robot by definition means that the risk of breaking down is lower given the same influence factors. A risk has two influence factors, the likeliness of happening and the severity of the consequences. If both factors are high, the risk is high and countermeasures should be found. If only one factor is high, there is a tradeoff between the benefits and the increased complexity of the appropriate countermeasures. In the following the type of the menace that poses a risk to a VSA is called threat.

Compared to a rigid robotic actuator the concept of VSA has two drawbacks, namely a built-in spring with a more complex dynamic behavior and an increased complexity in the mechanics including more parts. The risk of the more complex dynamic behavior of the VSA is severe damage by overload due to unwanted oscillations. The complex mechanics has an increased risk, because more parts more likely lead to a failure.

The multi-body dynamics of a flexible multi-DoF system such as the DLR Hand Arm System [7] (see Fig. 1) is extremely complex to handle. During motion, potential and kinetic energy swaps between the links within the system. These oscillations can superpose and result in much higher peak levels than the average single oscillation. If these energy peaks are larger than the maximum capacity of the spring, the corresponding actuator is likely to fail. Remedies for this are physical damping [9], damping by control [10], and dedicated control strategies like the optimal control approaches (see [5], [11]), which can be used not only for exciting the system but also for slowing it down.

In this paper, we present how the failure risks are acting on a 1-DoF VSA and how these could be counterbalanced by the hardware design and low level control. It is important to mention that these methods do not guarantee absolute

TABLE I: (Ext)ernal and (int)ernal threats for a VSA robot

threat type	drive train	structure	electronics	materials
mechanical	ext / int	ext / int	ext	ext
liquids	ext		ext	ext
electrical			ext / int	
thermal	ext / int		ext / int	ext / int
radiation			ext	ext
chemical			ext / int	ext / int

robustness. Also they cannot cover all kinds of control errors, especially if the VSA is working at its performance limits. However, they reduce the likeliness of damage to the system.

The main part of the paper is separated into three sections. Section II gives an overview of the possible threats to a VSA. This is followed by possible countermeasures to avoid damage to the VSA in section III. Both, the list of threats and the corresponding countermeasures can only be a subset of all possibilities, but we want to highlight those which have the highest risk according to our experience of the past years of work with VSAs. In section IV the reaction strategies are evaluated on the DLR Hand Arm System.

Many of the threats presented in Sec. II apply also to traditional rigid actuators. However, for sake of completeness all relevant threats and the corresponding countermeasures (Sec. III) on a VSA are briefly addressed. The countermeasures focus on the specialties of a VSA.

II. Threats on a Variable Stiffness Actuator

The risk of damage to a VSA can be separated into external and internal threats (see Table I). External threats are the threat of incidents with their origin from outside the VSA equipped robot. Internal threats can be described as self-destruction, which seem to be a little bit unlikely at first sight, but are in fact the bigger risk to high power systems like the DLR Hand Arm System.

A. External risks

External risks have their origin from outside the robot. This includes also events caused by the robot motion, but act on the robot from outside like when the robot collides with a still standing object, e.g., a table. There are six different domains of external threats:

- mechanical
- liquids
- electrical
- thermal
- radiation
- chemical

The IEC (International Electrotechnical Commission) invented the IP (Ingress Protection) classification system in IEC 60529, which is defining different levels of threats and associated protection from solid foreign objects and moisture. Whereas it covers the possible influence and levels of shielding against liquids, it is only a subset of the mechanical risks, namely the ingression of objects and dust.

However, it does not cover forces acting on the robot from outside. These forces may result in an overload in the structure or the drive train, e.g., gear, VSA spring, bearings, or mechanical end stop. The mechanics of a VSA is typically more complex and has more parts compared to a rigid actuator, which results in more sources of error. Furthermore, if external forces are applied locally on small areas, e.g., by sharp objects, the material stress limits of the affected part may be exceeded. Whereas the joint structure is usually quite robust the uncovered cables and electronics which are typical for mechatronic systems are prone to damage by mechanical impacts.

Liquids and dust may cause friction and wear in the mechanical components, they may even jam the joints and set them inoperable. They may also result in electrical shortcuts and in the worst case destroy the whole robot and even inflame its environment when overheating.

The electrical, thermal, radiation, and chemical influences affect mainly the electronics and the components materials themselves.

B. Internal risks

Internal risks result from the robot activation itself. A minor role play chemical risks coming form inside of the system. These are leakage of hydraulic fluid, cooling fluids, or electrolyte of batteries and capacitors. Usually internal risks are limited to three different domains:

- mechanical
- electrical
- thermal

Mechanical threats are primarily affecting the drive train. The energy in the motor inertia and the oscillating output has to be kept within the limits so that the actuator torque does not exceed the maximum of the gear, spring, other mechanism components, and the structure. Depending on the mechanical construction and spacial arrangement, the load limits of mechanical end stops and self collision have to be considered.

In our experience one of the most widespread cause of damage to the robots in research and development is an error in the programming and a resulting misbehavior of the robot. Then the controller acts in an uncontrolled way and the motor(s) typically move without control at their maximum performance. In this stage the aforementioned mechanical threats are very likely to be met.

The most common electrical threat resulting from inside the VSA is overvoltage resulting from the motor operating in generator mode. The motor is in generator mode when it tries to decelerate. The oscillating output may then result in torque peaks on the motor that result in voltage peaks generated by the motor. In case of deceleration mechanical energy has to be transformed into another domain, which is typically thermal or electrical. This transformation has to be kept within controlled limits.

The internal thermal threat is typically overheat in the motors or in the electronics. Especially when operating the motors in states exceeding nominal power and nominal load, the danger of self-destruction is eminent. In the case the thermal dissipation to the surrounding air and structure is less than the power losses in the motor. This surplus thermal energy can only be buffered in the thermal capacity of the motor elements until its level drops below the nominal state and is also dissipated. In addition this effect is self amplifying, because the efficiency of the motor drops with the temperature and as a result for the same mechanical output power the transformation losses are greater. The same effect applies to the power electronics: The higher the supplied currents are, the higher are the dissipations in wiring and electronic components and the less is their efficiency.

III. Protection Methods

In this section different methods to address the previously discussed threats are presented, so that the risk of damage is reduced. The methods are grouped in hardware, observation, control, and reaction methods.

In the hardware section the countermeasures in the design of a VSA robot are shown. The observation section describes how sensor information and system knowledge can be used to monitor the hardware and to detect erroneous behavior of the system. This helps to prevent additional and probably more severe damage. The control limits make use of sensor information to actively influence the control in case of undesired control input or system state. The reaction methods use higher system knowledge to actively change the system state in a way that the risk of damage is reduced.

A. Hardware

The first step to resist external threats is to apply a proper shielding. This is a simple, but effective solution to overcome most of the external influences. Usually a padding or housing is used against local mechanical impacts and thermal influences. Against chemicals, dust, and moisture, high voltages, and electromagnetic disturbances a seamless, resistant 'skin' is sufficient. This approach is constructively more demanding. Both solutions usually do not influence the weight too much, but have the drawback that the robot is getting a little bit larger. Both may have a negative influence on the range of motion, and the thermal dissipation to the environment. In consequence eventually a special cooling system is necessary. Covering a VSA robot is more demanding than a rigid robot, because the mechanics is more complex and larger in size. Especially high energy springs are big, bulky, and change their shape during movement which can be seen for example in walking machines like the ECD leg [12] or Phides from TU Delft [13]. Many VSAs use tendons in the transmission, which adds to the difficulty to covering and sealing the robots.

The influence of radiation is mainly critical to the electronics. A proper shielding to β- and γ-radiation is difficult or impossible without making the robot too bulky and exceeding the load limits of a common robot. Hence the electronics has to be designed to cope with radiation (see [14]).

Mechanical overload in the drive train may result from external impacts or simply by self induced oscillations and high dynamic motor movements. The principle of a VSA itself basically is a mechanical overload protection. The mechanical spring inside decouples the output from the gearbox and motor inertia. As long as the energy capacity of the spring is not exceeded and the drive train is designed to withstand the torques within this limit, the intrinsic properties of the VSA are sufficient. The energy capacity and maximum torque should be selected in a way that the maximum expected values during normal operation including a safety margin are within the specifications. However, the event of overload and the resulting consequences should be considered as well.

In case of overload occurring in the system, the weakest link in the chain from the motor to the output will break or at least be damaged. The best solution to avoid that problem would be an overload protection like a mechanical or sensor based torque limiter, both of which are commercially available. Both are a kind of clutch or release mechanism, which form a more or less stiff connection between two parts, and release when a certain torque limit is exceeded. Unfortunately such torque limiters are relatively heavy and bulky compared to current VSA implementations and the release torque is difficult to set precisely and reliable. As a result no current VSA is equipped with one of these systems.

Usually mechanical end stops are used to protect parts of the VSA by constraining the moving range. An end stop acts like a mechanical shortcut or bypass of the load around the protected segment of the drive train. Unfortunately the rest of the drive train, which is not bypassed, still has to withstand the load. In a VSA usually the spring has to be protected from overload. If the spring is bypassed by an end stop when reaching its flexibility limit, the decoupling of the output from the gear and motor is not given anymore. Without the spring buffer it is very likely that the torque rises very fast in this case and, e.g., the gear is overloaded and breaks.

The internal electrical threat is over-voltage in generator mode. This can be overcome by a power supply, which is capable to back-transform power to the input net. Another way is a crowbar that dissipates the generated energy in resistors. An electrical energy recovery system, which stores the generated energy in capacitors or batteries, is coherent to the VSA idea with the mechanical energy storage in the springs and increases the energy efficiency. The stored energy can be reused in later acceleration phases.

B. Observation

An observation of the system relies on sensor and model information and checks them for plausibility and errors. The position of a hardware-observation block in the control loop like it is used for the arm control of the DLR Hand Arm System is depicted in Fig. 2. The output of such a block is information on the system which may include the following:

- System is working properly
- Validity of each sensor signal
- Error in a specific system component
- Discrepancy of an observer model to the real system state

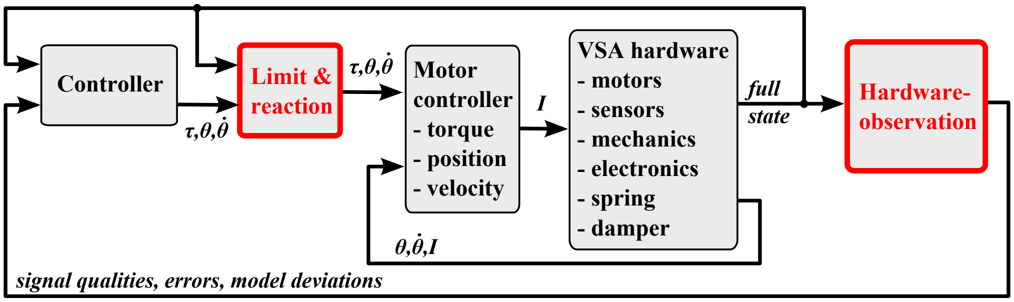


Fig. 2: Schematic of the controller setup with limiter and observation blocks. The motor controller regulates the motor current I by the motor position θ, motor velocity $\dot{\theta}$, or the motor torque τ. The hardware observation block investigates the sensor data for errors and deviations from models of the VSA hardware. The limiter is actively intervening the control signal when a defined limit is exceeded.

For further information on the surveillance and error detection of sensors and actuators see [15]. The controller uses this information to react accordingly. A simple, but most likely not the best solution is to switch off the Robot in case of an error occuring. This strategy is not necessary in many cases and causes extra down time of the whole robot system. A complex system like the DLR Hand Arm System for example has 52 motors, 112 position sensors, and many other sensor data. As a result it is very likely that one of the multiple signals is marked as erroneous, but this does not necessarily mean that the system cannot perform the task and has to be switched off. In addition to that, if the system is in a highly dynamic system state like throwing a ball, a sudden switching off bears the internal risk of heavy damage by the system, because of an overload in the joints (see Sec. II-B).

There are several observation strategies to extract extra information out of the pure sensor signals:

1) Interval check: Checking sensor values to be in the right interval. For position sensors to be within the joint limits, spring length limits, torque and current limits of the motors, valid temperatures etc.

2) Redundant sensors: Using information of redundant sensors, e.g., a motor encoder and a position sensor at the gear output.

3) Mechanical loop: Using sensors in a mechanical loop with different position signals. If the sum of positions has any larger deviation, this is a hint of a broken part or sensor. VSAs usually utilize more sensors than rigid robots, which are able to gain more data for the investigation. One example for this can be seen in the sensor map of the DLR FSJ (see Fig. 3), which is the VSA of the first 4 axes (shoulder and elbow) of the DLR Hand Arm System.

4) Plausibility: Checking the plausibility of the sensor values and their rough correspondence with physics, like large jumps of position signals. If the acceleration of motor position is significantly greater than the maximum acceleration of the motor inertia $\tilde{m}$ caused by the sum of motor torque τ_{main} plus external torque τ_{ext}, it is likely to be an error (In the following, motor side variables before the gear are marked with a tilde). For the main motor of the FSJ this is, if

$$\ddot{\tilde{\theta}}_{\mathrm{main}} \gg (\tau_{\mathrm{main}} + \tau_{\mathrm{ext}}) \, \frac{\tilde{m}}{n} \, , \tag{1}$$

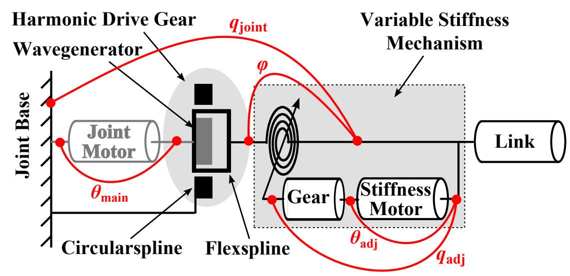


Fig. 3: Position sensor map of a VSA on the example of the DLR FSJ. Sensors are represented as red lines connecting the referenced parts. The information of redundant sensors and sensors in a mechanical loop can be used to detect errors. In the example sensors measure the position before θ_{adj} and after the gear q_{adj} of the stiffness adjusting motor and in the mechanical loop of main motor position θ_{main}, output position q_{joint} and passive spring deflection φ.

with the acceleration of the main motor $\ddot{\tilde{\theta}}_{\mathrm{main}}$ and the gear ratio n.

5) Observer model: Using a dynamic model of the VSA in an observer model and check for discrepancy to the measured state. This may be also a thermal model with the motor and supply currents as input and temperature sensors as reference.

C. Control limits

The next step is to add active software limits. Such a limiter block (limit & reaction) (see Fig. 2, is placed in between the actual VSA- or robot-controller (further called controller) and the motor controller.

The intended features of this block are that it does not affect the control during normal operation independent to the controller, and that it is modular expansible to new software limitations and other hardware.

The proposed limiter block is passing through the controller signal as long as the given software limits are not exceeded (see Fig. 4). The layout is separated in steps. Each step implements one software limit. It may be the case that some of the limits are conflicting with each other. Thus it is better to implement the limits not in parallel, but in a ascending hierarchy of importance. The limits for events that most likely result in a serious damage of the system like end stops are put as the last steps in that order. Other limits, which are precautions or do not harm the system instantly like constant maximum velocity are the starting steps, so that they can be overruled by the more important limits.

Each step is only active, when the corresponding limit is exceeded. In this case, a function, that has the deviation of the actual state from the limit as an input, puts a bias on the desired controller signal. The function generates the bias so that the investigated system state, e.g., motor torque, position, and velocity, stays within the limits. This bias can increase until the controller input is completely overruled. The limiters before and after each step in the flow chart (see Fig. 4) ensure that the maximum desired value never exceeds the control range. The following limiter step is then able to overrule the previous signal completely in the case of its bias function being greater than the full control range. With the presented structure the active step takes over automatically without any need of controller switching. The controller runs in the background until the actuator state is back within the desired region.

Different hardware implementations require different limitations of the VSA. Typical limits are:

- Motor torques
- Motor positions interval
- Spring pretension (if applicable)
- Co-contraction of antagonistic VSAs (if applicable)
- Motor velocities
- Output position limit

In the following the aforementioned limitations for a VSA are presented in more detail.

1) Motor torque limit: The motor torque limit is a simple limit on the motor torques and is in consequence also limiting the static output torque of the VSA. The use of this limit may be to ensure lower accelerations and the ability to prevent the robot from movements by pushing it manually. Another application may result from thermal restrictions. Lower torques mean lower currents in the motors and electronics, thus the resulting thermal losses are reduced. A thermal model can be exploited to generate an adapted torque limit to prevent overheat.

2) Motor position limit: If there are hardware end stops on the motor position it has to be ensured that the motor does not run into these limits. Since the end stops are usually positioned after the gearbox, the reflected motor inertia $m_{\text{reflected}}$ is

$$m_{\text{reflected}} = n^2 \tilde{m} \tag{2}$$

The inertia is scaled quadratically by the gear, whereas the velocity is scaled only linear. As a result, in actuators with a high gear ratio the reflected inertia becomes very big. In the case of the FSJ [8] of the DLR Hand Arm System it is in the same order of magnitude as the link side inertia. This means that in case the motor is running into the hardware end stops at significant speed the end stop and also the gear are highly stressed. Therefore it is mandatory that the motor position stays in a certain interval of position. Usually the selected interval in which it is held by the control or by the

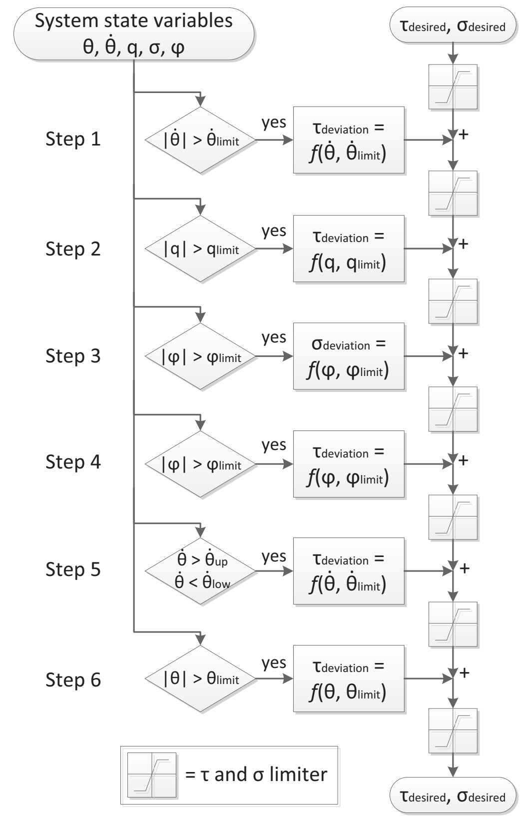


Fig. 4: Flow chart of the limit and reaction block for a torque τ and stiffness setup σ controlled VSA on the example of the implementation for the DLR Hand Arm System. The desired values coming from the higher level controller are modified by this block according to the different limits and reactions. The structure constitutes a hierarchy from the least important (top of chart) to the most important (bottom of chart).

limiter block is a little bit smaller than the hardware limits are (see Fig. 5). The functionality of the limiter block is given by adding a torque in the opposite direction if the software limits are exceeded.

3) Spring pretension limit: Spring pretension is used in many VSAs to vary the actuator stiffness. Here a dedicated motor is giving the pretension to the spring. The resulting limit is the same as for the motor position interval.

4) Co-contraction limit: A limit on the co-contraction $\triangle\theta_{\text{contract}}$ of antagonistic VSA is also a limit on a motor position interval, but here the interval has dynamic limits. One of the two opposing motors has to be defined as the master motor and the other one as the slave. The slave motor is then limited in its position θ_{slave} relative to the master motor position θ_{master} . For bidirectional antagonistic systems, where each motor can push and pull, it is

$$\theta_{\text{master}} - \triangle\theta_{\text{contract}} < \theta_{\text{slave}} < \theta_{\text{master}} + \triangle\theta_{\text{contract}} \tag{3}$$

and for antagonistic systems where both motors can only pull it is

$$\theta_{\text{master}} - \triangle\theta_{\text{contract}} < \theta_{\text{slave}} < \theta_{\text{master}} \,. \tag{4}$$

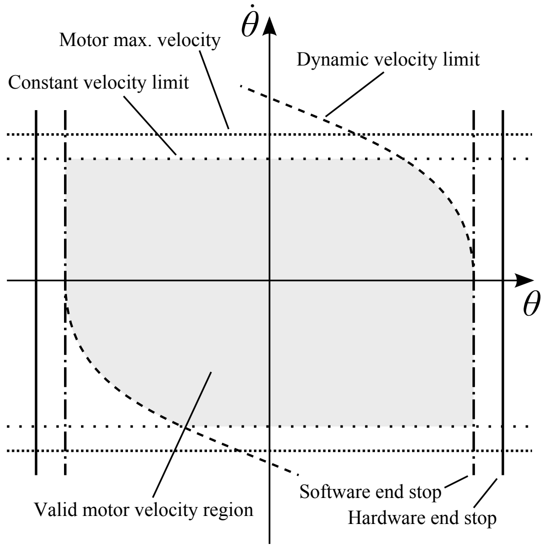


Fig. 5: The safe region of motor velocities $\dot{\theta}$ vs. the motor position θ is depicted in grey. The software end stop is usually placed with a safety margin before the hardware end stops. A constant velocity limit is setting upper and lower bounds to the motor velocity which may be needed, e.g., due to gear velocity restrictions. The dynamic velocity limit ensures that the motor is capable of slowing down before the software end stop with its maximum braking torque. The braking torque can be either the maximum motor torque, the torque of a physical brake, or both of them.

In the limiter structure of Fig. 4 the co-contraction limit would be integrated as an extra step with a torque deviation only on the slave motor.

5) Static motor velocity limit: There are two ways of motor velocity control. The first is to simply limit the velocity to a given level. This may be because of safety concerns, gear velocity limits, or a better predictable interaction with the robot. In order to achieve this the limiter block adds torque in the opposite direction of the velocity to decelerate the motor in case the limit is reached.

6) Dynamic motor velocity limit: The second way is a dynamic velocity limit which ensures that the motor inertia can be stopped with the maximum braking torque $\tilde{\tau}_{\max}$ before the software end stop is approached (see also Fig. 5). This is important, because even with the high torque RoboDrive Motors of the FSJ it takes a significant time and in consequence motor angle to stop the motor from maximum velocity. For the calculation of the dynamic limit it is assumed that the spring of the VSA decouples the output inertia form the motor inertia. Furthermore, it is assumed that the braking torque $\tilde{\tau}_{\max}$, which is the motor torque, the torque of a physically implemented brake, or the sum of the two is constant. This can be assumed as true for the RoboDrive motors of the FSJ. For sake of simplicity friction and damping are neglected, which is a worst case assumption, because both effects increase the braking torque.

With the constant braking torque the deceleration of the motor is

$$\ddot{\tilde{\theta}}_{\text{limit}} = \frac{\tilde{\tau}_{\max}}{\tilde{m}} \tag{5}$$

which is at the gear output

$$\ddot{\theta}_{\text{limit}} = \frac{\ddot{\tilde{\theta}}_{\text{limit}}}{n} \,. \tag{6}$$

The braking time is

$$t = \frac{\dot{\theta}_{\text{limit}}}{\ddot{\theta}_{\text{limit}}} \tag{7}$$

and the braking angle

$$\triangle\theta = \frac{1}{2}\,\ddot{\theta}_{\text{limit}} t^2 = \frac{\dot{\theta}^2_{\text{limit}}}{2\,\ddot{\theta}_{\text{limit}}} \,. \tag{8}$$

Solving for $\dot{\theta}_{\text{limit}}$ results to

$$\dot{\theta}_{\text{limit}} = \pm\sqrt{|2\,\triangle\theta\,\ddot{\theta}_{\text{limit}}|} \,. \tag{9}$$

With the upper position limit θ_{up} and the lower position limit θ_{low} the braking angle is

$$\triangle\theta = \theta_{\text{up}} - \theta \tag{10}$$

and

$$\triangle\theta = \theta_{\text{low}} - \theta \,, \tag{11}$$

respectively. So the upper velocity limit is

$$\dot{\theta}_{\text{up}} = \sqrt{|2\ (\theta_{\text{up}} - \theta)\ \ddot{\theta}_{\text{limit}}|} \tag{12}$$

and the lower velocity limit

$$\dot{\theta}_{\text{low}} = -\sqrt{|2\ (\theta_{\text{low}} - \theta)\ \ddot{\theta}_{\text{limit}}|} \,. \tag{13}$$

With (5), (6), and $\tau_{\max} = n\,\tilde{\tau}_{\max}$ we get

$$\dot{\theta}_{\text{up}} = \sqrt{|2\ (\theta_{\text{up}} - \theta)\ \frac{\tau_{\max}}{\tilde{m}}|} \tag{14}$$

as the upper velocity limit and

$$\dot{\theta}_{\text{low}} = -\sqrt{|2\ (\theta_{\text{low}} - \theta)\ \frac{\tau_{\max}}{\tilde{m}}|} \tag{15}$$

as the lower velocity limit.

D. Reaction

The previously described control limits are of the type that they prevent an unwanted or potentially harmful action that the controller commands. As the name implies they are limiting and not acting actively. In some situations it may be desirable that there is an active reaction of the system analogous to the reflexes of a human. In the following, two kinds of reactions are presented.

As previously noted in Sec. III-A one of the problems in the drive train is what to do when the spring deflection limit is approached. In order to avoid this an extremely big spring could be utilized, which would be of no use during the normal operations and would increase weight and bulkiness. An alternative is to actively move the VSA position in the direction of the threatening torque, so that the spring is discharged. This for example can be initiated at a load level above a certain percentage of the maximum torque, a given remaining potential energy capacity in Joule, or a remaining passive deflection angle. For the latter case the reaction is active when

$$|\varphi| > \varphi_{\text{limit}}(\sigma) - \varphi_{\text{react}}, \tag{16}$$

with the desired remaining passive deflection angle φ_{react} and the passive deflection limit $\varphi_{\text{limit}}(\sigma)$ which is dependent on σ in the case of the FSJ. This reaction is depicted in step 4 in Fig. 4.

Another reaction (step 3 in Fig. 4) that addresses the same threat takes advantage of the capability of a VSA to change its stiffness. It uses the same activation criteria as the previous reaction. Depending on the construction and the implementation principle, a VSA features different spring energy capacity or maximum deflection angle at different stiffness presets. If the VSA is set to a less advantageous stiffness preset concerning these points, this can be used in the reflex. As long as the threat of overload is present the VSA changes the stiffness preset and returns to the normal state when the critical situation is over.

Spring preload type and antagonistic VSAs have a higher energy capacity at lower stiffness presets, because the energy used to preload the spring(s) for a stiffer setup can not be used for passive deflection. In this case the motors release the preload during the reflex so that they do not have to supply extra power and at the same time increase the actuator energy capacity. An additional benefit is that also the maximum passive deflection angle increases with a softer stiffness preset.

IV. Evaluation

In this section the reactions of Sec. III-D are evaluated with impacts on the DLR Hand Arm System. For the tests the arm is moved to an outstretched position to the front in order to give a preload to shoulder and elbow by the gravitational force. The arm is held on this position with PD control and then a steel ball is dropped into the hand, which results in an impact on the arm (see Fig. 6).

Fig. 6: Setup of the impact test on the DLR Hand Arm System. The steel ball is dropped on the hand, resulting in an impact on the arm.

For this test, we investigated the influences of the impact on the shoulder joint, which is the first axis in the kinematic chain. In the outstretched position the gravitational torque is $35.4\,Nm$. The steel ball has a weight of $510\,g$ and a falling height of $0.460\,m$, which results in the difference of the potential energy of $2.3\,J$. This energy is transferred to the arm during the impact and affects the shoulder axis together with the additional gravitational load of the ball ($4\,Nm$).

The reactions on the motor position θ and the stiffness setup σ are active, when the remaining passive deflection angle is less than $2\,°$. The stiffness setup is set to a value of 50% of the maximum value. The stiffness setup and the desired remaining passive deflection angle result in a reaction when φ is grater than $7.9\,°$. For lower φ the reactions are not active in the system.

In Fig. 7 the response of the shoulder actuator to the impact is shown. The diagrams from left to right are showing the different types of possible reactions. The different cases are

(a) no reaction
(b) motor position θ reaction
(c) stiffness preset σ reaction
(d) motor position θ and stiffness preset σ reaction

The plots in the upper row show the system behavior of the passive deflection angle φ and the limit on the deflection angle φ_{limit}. In the lower row the remaining potential energy of the spring is plotted.

It clearly can be seen that the reactions significantly increase the remaining energy capacity during the impact. With the θ reaction the capacity can be increased by $1\,J$ and with the σ reaction by $0.5\,J$. The combination of the two reactions only results in a slight improvement over the θ reaction. The effect of the σ reaction increasing the passive deflection angle limit φ_{limit} can be seen in Fig. 7c and 7d.

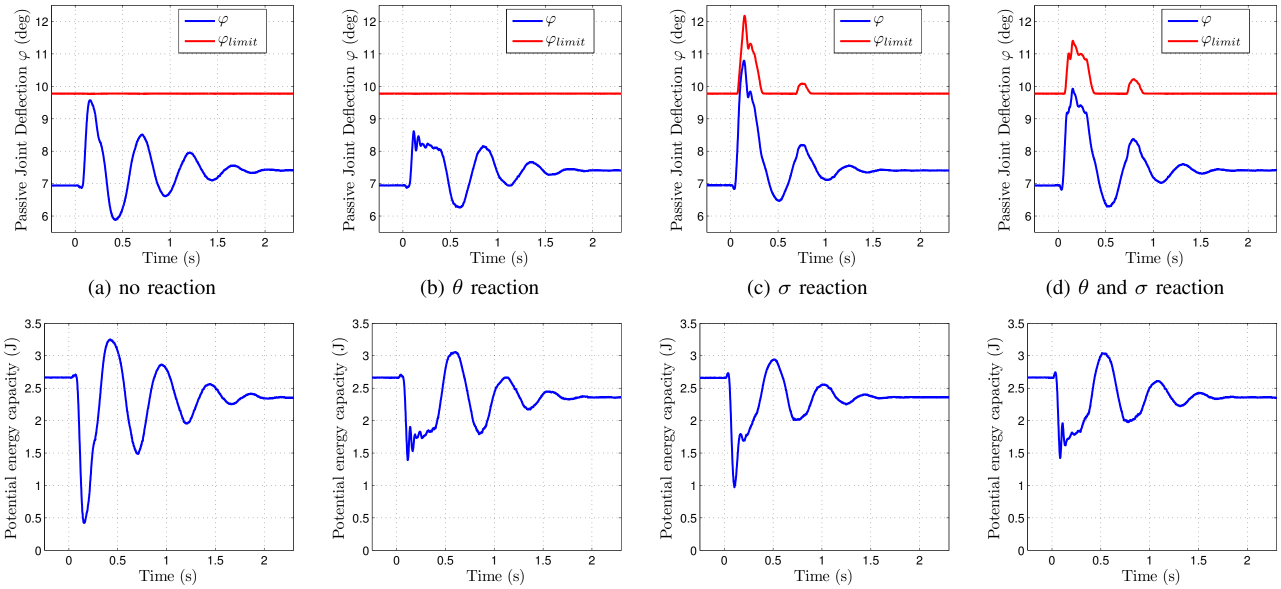
The effect of the combination of the strategies having such a low influence on the σ reaction can be tracked back to two different reasons in the opinion of the authors. Both have their origin in the different size of the two motors of the FSJ. The first reason is that the main motor with a peak power of $1080\,W$ is able to accelerate significantly faster than the stiffness adjuster motor with a peak power of just $192\,W$. The second reason is that the maximum velocity of the main motor with $680\,°/s$ at the output is much higher than the maximum velocity of the stiffness actuator, which affects the maximum deflection angle with a velocity of $36\,°/s$. As a result the θ reaction is the dominating factor in this setup.

The effect of σ reaction will be higher in a VSA-setup with a more powerful stiffness actuator, or during a stronger impact when the θ reaction is not sufficient anymore. Experimental validation of the latter case is part of future work.

V. Conclusions

The first step towards a more robust VSA robot is started with the identification of possible threats to the robot. Threats to the robot do not only reside in the environment. Especially high performance robots have to counteract self generated risks in order to not harming them-selves. The threats are identified to origin from different domains and are separated into internal and external ones. Appropriate protection methods are developed to cope with the identified threats.

At first different hardware design aspects are discussed. Afterwards the possibilities of a sophisticated observation of the sensors values and sensor based models are addressed. Different control limiters ensuring the limits of positions, velocities, and other aspects are presented. Active reactions



(a) no reaction (b) θ reaction (c) σ reaction (d) θ and σ reaction

(e) no reaction (f) θ reaction (g) σ reaction (h) θ and σ reaction

Fig. 7: Reaction strategies on an impact result in a reduction of peak load. The remaining passive joint deflection and energy capacity are bigger with a active reaction. The reaction on the main motor position θ is in this test more effective than the reaction on the stiffness setup σ. The combination of the two reactions is the most effective, but has only a slight improvement over the θ reaction.

are proposed as an augmentation to the control limits. These contribute to the reliability of a VSA as they reduce the likelihood of overload in the spring mechanics. The reactions were evaluated on the DLR Hand Arm System and show a good performance as they significantly improve the behavior during an impact.

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