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A Model-Free Approach to Vibration Suppression for Intrinsically Elastic Robots

Florian Petit[1,2], Christian Ott[1] and Alin Albu-Schäffer[1]

***Abstract*— Robots with joint elasticity find increasing interest in many research areas. A common design goal is to achieve as little mechanical joint damping as possible. To still achieve system damping often control systems are used. Here, we present a model-free approach to achieve damping via exploiting the kinetic to potential energy transformation process of the robot mass and the joint elasticity. The controller acts in an energetically passive way and is applicable to multi-joint systems. The theoretical findings and simulations are substantiated by experiments on the DLR Hand Arm System.**

I. Introduction

The introduction of passive elasticity in robot joints is a popular way to increase performance. Mechanical springs are implemented in many types of robots at various scales. In general, elastic elements are able to store energy. Thereby, several advantages may be achieved. The robustness with respect to impacts can be increased as the link mass and joint elasticity yield a mechanical low pass filter. This is very relevant for robotic hands, where rigid impacts occur on a regular basis [1]. The energy storage capability can be exploited to perform dynamic motions. Some legged robots [2] exploit this fact. Furthermore, energy efficient motion generation is also discussed in this context [3], to name a few.

A multitude of compliant robots have been designed. We focus here on joints which are electrically driven (and predominantly intended for the use in robotic arms). A first push towards elastic robot joints is the series elastic actuator (SEA) concept [4]. A main focus of this development was the ability to control joint torques using spring deflection measurements. Based upon this technology, an upper body system has been designed [5] and it even constitutes the basis for a commercial product [6]. Since then, especially the variable stiffness actuation (VSA) concept has been the focus of many researchers. It enables applications where elastic energy storage is exploited. Additionally, the joint stiffness can be varied and thereby adapted to the task. A possible scenario is resonance tuning for a locomotion gait [7]. Historically, the stiffness adaptation idea can be allocated to the efforts of the robotics community to embed more functionality into hardware mechanisms themself, called task embodiment.

[1] Institute of Robotics and Mechatronics, German Aerospace Center, Oberpfaffenhofen, 82234 Wessling
[2] Sensory-Motor Systems Lab, ETH Zürich, 8092 Zürich, Switzerland
[2] Corresponding author: Florian.Petit@dlr.de
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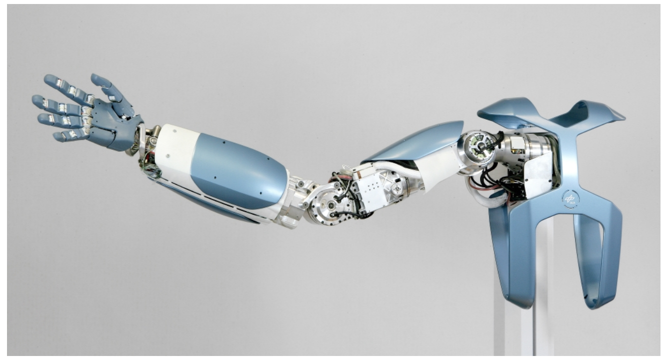

Fig. 1. The DLR Hand Arm System.

Some examples for elastic systems are the multi joint robots DLR Hand Arm System [8] or the CompAct™ arm [9]. These robots are high end prototype systems, built with substantial monetary effort. At the other range of the financial spectrum are systems such as the Maccepa joints [10] and recently the QBoid platform [11]. The last two systems are intended to provide simple to use and affordable robot joints.

It is common for all the described systems that the joint elements inhere as little damping as possible. This is very beneficial, as torque measurement quality is increased, dynamic motions are supported, and high energy efficiency is achieved. However, the lightly damped SEA and VSA systems tend to show oscillations which is not desired during e.g. tracking and manipulation tasks. As a result, damping needs to be injected. Some mechanisms provide damping on a physical level [9]. Another popular approach is to use feedback control. The main advantage of the control system solution is that the joint actuators are usually powerful enough to provide the damping action and therefore no additional mechanical device is needed.

Several solutions for joint damping controllers have been reported in the literature. Well known approaches such as feedback linearization [12], linear-quadratic regulators [13], learning control schemes [14], or modal based state-feedback controllers [15], have been developed. Many of these schemes are highly effective and provide great performance. A constraint of these approaches is their reliance on a good mathematical robot model. On the one hand, this enables the theoretical control process and guarantees good performance. On the other hand, models are always prone to errors, stemming from imprecisions in the representation itself and/or parameter inaccuracies. Due to strong variations of dynamic properties (e.g. inertia and stiffness) of a whole arm, model based approaches which try to strongly change the dynamics by imposing a simple desired dynamics (e.g. feedback linearization) lead to strong variations of the controller gains. This, in turn, often leads to instability due to noise or unmodeled dynamics. Additionally, the high dimensionality of the robot model - a standard robotic arm consists of seven degrees of freedom (DOF) - is challenging for some of the controllers such as the LQR approach [13]. At least, real-time control at a high rate (> 1 kHz) poses quite high demands on the computational infrastructure. For high end prototypes these requirements are often easier to fulfill as robot design data can be obtained, powerful computational infrastructure is present, and sensory information are highly precise. This is often contrary for the cost effective systems and complex model based control approaches are then foreclosed. But still the need for damping control is present.

In the following we present a model-free damping control approach, which complies with the necessity of a simple yet effective damping controller. The approach makes use of the joint elasticities to convert kinetic energy injected by disturbances into elastic energy, which is then dissipated by the joint actuators. The approach only requires state information of the robot. It is easy to implement, has low computational demands, and is also applicable for multi-joint robots. It can be applied on both, torque controlled and position/velocity controlled systems. The control system is energetically passive and exploits the natural mechanical response of the robot hardware. Therefore, it is well suited for human-robot interaction tasks.

The paper is organized as follows. First, the damping problem is specified in Section II. The controller concept is given in Section III. To be applied in general elastic robots the concept is extended, see Section IV and Section V. There, also simulations of the closed loop system are given. An experimental evaluation has been conducted on the DLR Hand Arm System and its results are given in Section VI. Finally, the controller properties are discussed in Section VII and a conclusion is given in Section VIII.

II. Problem Statement

It turns out that a large number of elastic joint robots, all mentioned in this paper, can be modeled by

$$\begin{aligned}\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{g}(\boldsymbol{q}) &= \boldsymbol{f}(\boldsymbol{\varphi},\boldsymbol{\sigma}) \\ \boldsymbol{B}\ddot{\boldsymbol{\theta}} + \boldsymbol{f}(\boldsymbol{\varphi},\boldsymbol{\sigma}) &= \boldsymbol{\tau}_m. \end{aligned} \tag{1}$$

The variable $\boldsymbol{q} \in \mathbb{R}^n$ is the link coordinate and $\boldsymbol{\theta} \in \mathbb{R}^n$ the motor coordinate. The main motor control input is $\boldsymbol{q} \in \mathbb{R}^n$. $\boldsymbol{\varphi} = \boldsymbol{\theta} - \boldsymbol{q}$ is the deflection between the motor and the link and $\boldsymbol{\sigma} \in \mathbb{R}^n$ is an additional control input, used for stiffness adjustment. The model consists of the rigid body dynamics with the inertia matrix $\boldsymbol{M}(\boldsymbol{q}) \in \mathbb{R}^{n\times n}$, the Coriolis and centrifugal terms $\boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}}) \in \mathbb{R}^{n\times n}$, and the gravity vector $\boldsymbol{g}(\boldsymbol{q}) \in \mathbb{R}^n$. Furthermore, the motor dynamics is defined by the motor inertia matrix $\boldsymbol{B} \in \mathbb{R}^{n\times n}$. The coupling between the motor and link is realized by elastic elements

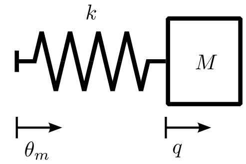

Fig. 2. A simplified robotic joint with a link mass M with coordinate q and a linear spring k. The input is the motor position θ_m.

$\boldsymbol{f}(\boldsymbol{\varphi},\boldsymbol{\sigma}) \in \mathbb{R}^n$. These elements are assumed to act joint wise[1] and can show a variety of characteristics: SEA actuators show a linear stiffness $\boldsymbol{f}(\boldsymbol{\varphi}) = \boldsymbol{K}\boldsymbol{\varphi}$ with $\boldsymbol{K} = \mathrm{diag}(\boldsymbol{k})$, the CompAct™ modules have a linear variable stiffness $\boldsymbol{f}(\boldsymbol{\varphi},\boldsymbol{\sigma}) = \boldsymbol{K}(\boldsymbol{\sigma})\boldsymbol{\varphi}, \boldsymbol{K}(\boldsymbol{\sigma}) = \mathrm{diag}(\boldsymbol{k}(\boldsymbol{\sigma}))$, and the FSJ joints of the DLR Hand Arm System have a progressive stiffness shape $\partial \boldsymbol{f}/\partial\boldsymbol{\varphi} > \mathbf{0}$, $\partial^3 \boldsymbol{f}/\partial\boldsymbol{\varphi}^3 > \mathbf{0}$ for all $\boldsymbol{\sigma}$. Since many of the mentioned systems can be modeled by (1), we refer to this model as the 'general VSA' model in the following.

Low mechanical damping is desired to enable the mentioned static and dynamic properties. Damping is added by control. The following section introduces the basic concept of the model free damping controller.

III. Controller: Basic Concept

To explain the controller idea, a flexible single joint in the absence of gravity as it is sketched in Fig. 2 is given. The robot is assumed to be in the static state where the spring is completely relaxed. Furthermore, the motor is position controlled as used to execute a positioning task. This simplified system can be modeled by

$$M\ddot{q} = k(\theta_m - q), \tag{2}$$

where θ_m is the motor position. A short disturbance impulse acting on the link will accelerate the link and thereby induce kinetic energy into the system. The elastic element is naturally resisting the disturbance and decelerating the link. In this process the kinetic energy is transformed into potential energy and stored in the spring. The mechanical energy is given by

$$V = U + T = \frac{1}{2}k(\theta_m - q)^2 + \frac{1}{2}M\dot{q}^2. \tag{3}$$

As the system is undamped, the system energy is constant and oscillations occur infinitely. The goal to stop the oscillation can be achieved by removing all the energy out of the system. A main point of the concept is the observation that there exist points on the oscillatory trajectory, where the system energy V is given completely by the potential energy expression U, see Fig. 3. This allows to derive a simple yet effective damping control law: By commanding a position jump of θ_m to q at times when $\dot{q} = 0$, the system energy can

[1]Biarticular joint couplings, as they exist in humans, are not implemented for the discussed robots. Still, the presented approach can be easily extended to be valid for coupled (biarticular) joints.

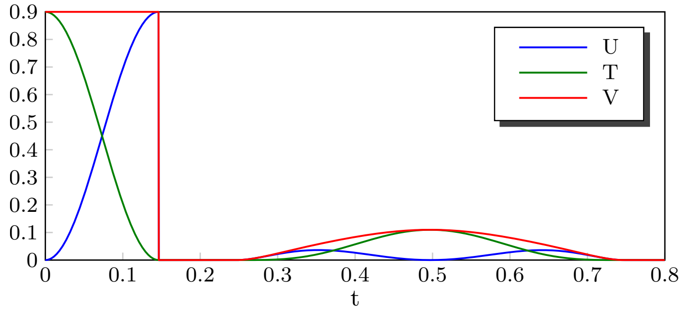

Fig. 3. The kinetic and potential energy of the disturbed system (2). The initial kinetic energy (initial link velocity, see also Fig. 4) is transformed into potential energy by the spring. Once the link is at rest, the controller kicks in and removes the complete energy, effectively suppressing oscillations. To re-establish the original link position a bring back motion is performed.

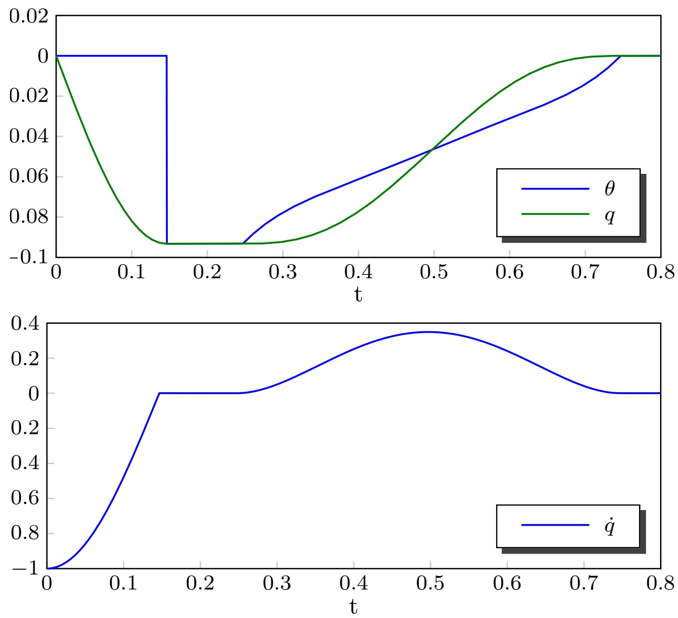

Fig. 4. The states of the system (2). After a disturbance, the motor position is held constant and the initial link velocity is continuously reduced by the elastic element action. Once it is zero $\dot{q} = 0$, the controller kicks in and removes the potential energy by setting $\theta_m = q$. Afterwards, a bring-back motion re-establishes the desired system state.

be completely removed to $V = 0$, see Fig. 4. No oscillations occur anymore. The control law is

$$\theta_m = q \quad \text{if } (\theta_m - q) \neq 0 \;\&\; \dot{q} = 0. \tag{4}$$

As the system is at rest now, the damping goal is fulfilled. To also re-establish the desired goal position, the system state has to be brought back. This bring back task is easier to achieve, as the system is in a static state, see Section IV-D.

To sum up, after a link disturbance the controller holds the motor position and uses the elastic element passively to transform the system energy. At the right time, when all the energy is potential, the motor relaxes the spring, thereby removes the energy and damps the system. Afterwards, the desired system state is re-established by a bring back controller.

IV. Controller: Setup

The controller concept from Section III needs to be adapted to be implemented on a real general elastic system (1). Such a system provides a torque input which allows to implement a position interface on the motor position by a PD controller. Thereby, the equilibrium position can be set, also under the influence of the gravity potential, see [16]. Still, the motor dynamics hinder to achieve position jumps of the motor position. In the following, we extend the damping idea to a motor velocity controlled system. This reflects practical confinements like limited motor velocity and is a good approximation to the PD-controlled system (1).

A. Velocity input damping law

The velocity input model of a general VSA system is given by

$$\begin{aligned} \boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{g}(\boldsymbol{q}) = \boldsymbol{f}(\boldsymbol{\varphi},\boldsymbol{\sigma}) = \boldsymbol{\tau} \\ \dot{\boldsymbol{\theta}} = \boldsymbol{u}, \end{aligned} \tag{5}$$

where $\boldsymbol{u} \in \mathbb{R}^n$ represents the input to the system. The controller idea to suppress oscillations by removing energy from the system at states where the kinetic energy is low. The mechanical system energy is given by

$$\begin{aligned} V &= U + T \\ &= U_{\boldsymbol{\tau}} + U_{\boldsymbol{g}} + \dot{\boldsymbol{q}}^T \boldsymbol{M}(\boldsymbol{q})\dot{\boldsymbol{q}} \end{aligned} \tag{6}$$

where $U_{\boldsymbol{\tau}}$ is the energy of the spring and $U_{\boldsymbol{g}}$ the energy of the gravitation potential. The time variation of the energy function is given by

$$\begin{aligned} \dot{V} &= \frac{\mathrm{d}U_{\boldsymbol{\tau}}}{\mathrm{d}t} + \frac{\mathrm{d}U_{\boldsymbol{g}}}{\mathrm{d}t} + \dot{\boldsymbol{q}}^T \boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \frac{1}{2}\dot{\boldsymbol{q}}^T \dot{\boldsymbol{M}}(\boldsymbol{q})\dot{\boldsymbol{q}} \\ &= \boldsymbol{\tau}^T(\dot{\boldsymbol{\theta}} - \dot{\boldsymbol{q}}) + \boldsymbol{g}(\boldsymbol{q})^T\dot{\boldsymbol{q}} + \dot{\boldsymbol{q}}^T(\boldsymbol{\tau} - \boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} - \boldsymbol{g}(\boldsymbol{q})) + \\ &\quad \frac{1}{2}\dot{\boldsymbol{q}}^T \dot{\boldsymbol{M}}(\boldsymbol{q})\dot{\boldsymbol{q}} \\ &= \boldsymbol{\tau}^T\dot{\boldsymbol{\theta}}. \end{aligned} \tag{7}$$

From (7) and the mechanical joint stiffness properties it follows, that the system energy is reduced whenever

$$\dot{V} \leq 0 \quad \text{if } \dot{\boldsymbol{\theta}}^T(\boldsymbol{\theta} - \boldsymbol{q}) \leq \boldsymbol{0}. \tag{8}$$

According to (8) energy is always dissipated if the spring is getting relaxed. The controller exploits this and damps the link side at the same time: To achieve strong link side deceleration, the motor position is not relaxing the spring instantaneously but holds its position and the controller just kicks in when the link is at rest. Thereby, first the link is stopped and then the system energy is removed. The velocity control law to release energy is given by (c.f. (4) and Fig. 5)

$$\boldsymbol{u} = \begin{cases} < \boldsymbol{0} & \text{if } (\boldsymbol{\theta} - \boldsymbol{q}) > \boldsymbol{0} \;\&\; \dot{\boldsymbol{q}} \geq \boldsymbol{0} \\ > \boldsymbol{0} & \text{if } (\boldsymbol{\theta} - \boldsymbol{q}) < \boldsymbol{0} \;\&\; \dot{\boldsymbol{q}} \leq \boldsymbol{0} \\ \boldsymbol{0} & \text{else.} \end{cases} \tag{9}$$

A control cycle proceeds a follows. A disturbance deflects the link. The induced kinetic energy is transformed into

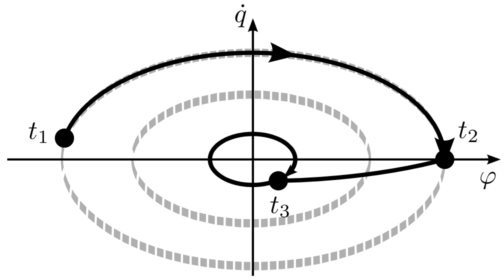

Fig. 5. Phase plots of the system (5) and the velocity damping controller (9). The grey ellipses are energy levels and the black curve is the trajectory. After an initial disturbance at t_1 the motor position is held, until the link is decellerated by the spring t_2. Then, the spring is relaxed by a motor trajectory in finite time t_2-t_3. This releases parts of the potential energy and damps further oscillations. To completely remove all the system energy, controller has to be repeatedly applied (after t_3).

potential energy in the spring. At the point, where the joint elastic element is maximally tensioned, the motor is controlled to move towards the link and thereby reduces the system energy. To avoid injecting energy into the system again, the motor is stopped once the spring is relaxed. As the motor velocity is limited in the practical case, the controller will not be able to bring the system to a complete rest. Nevertheless, a certain amount of energy will be dissipated and thereby a damping action is achieved. To completely dissipate the system energy, the controller is repeatedly applied. Once the system is at rest and thereby in a well specified state, an additional strategy is used to bring the system state back to the desired state. Possible alternatives are discussed in Section IV-D.

B. Velocity input damping controllers

The velocity control law (9) is providing qualitative bounds on how to achieve a damping behaviour of the controller. As similar for many control concepts, it provides room for quantitative interpretation, which can be compared to gain design. Gain design rules normally depend not only on theoretical considerations but also on practical and user or task specific needs. Therefore, we provide here two possible controller designs, discuss their properties and show simulation results.

1) State Proportional Control: A solution inspired by (9) is

$$\boldsymbol{u} = \begin{cases} -\boldsymbol{k}_u(\boldsymbol{\theta}-\boldsymbol{q})\dot{\boldsymbol{q}} & \text{if } (\boldsymbol{\theta}-\boldsymbol{q}) > \boldsymbol{0} \;\&\; \dot{\boldsymbol{q}} \geq \boldsymbol{0} \\ \boldsymbol{k}_u(\boldsymbol{\theta}-\boldsymbol{q})\dot{\boldsymbol{q}} & \text{if } (\boldsymbol{\theta}-\boldsymbol{q}) < \boldsymbol{0} \;\&\; \dot{\boldsymbol{q}} \leq \boldsymbol{0} \\ \boldsymbol{0} & \text{else.} \end{cases} \tag{10}$$

Herein, $\boldsymbol{k}_u$ is a constant gain value. An advantage is the smoothness of the control law caused by the smoothness of the state variables. To demonstrate the velocity input damping controller, it was tested on a one joint system (1) with the parameters

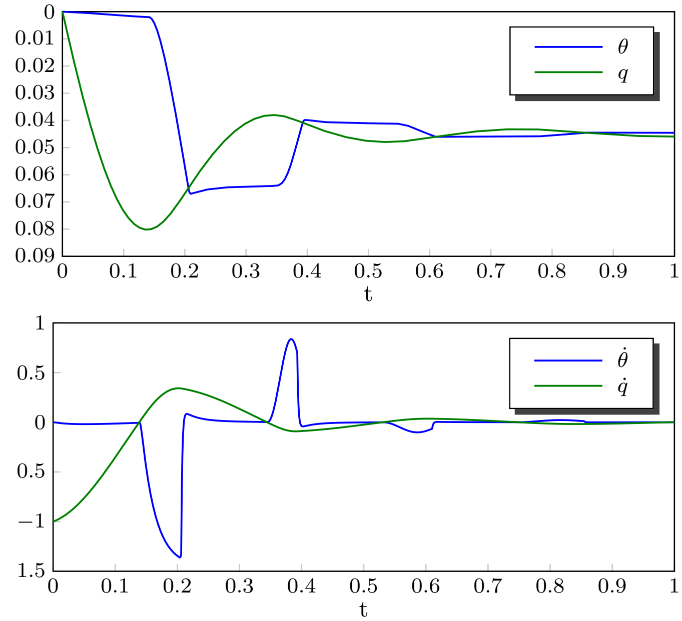

Fig. 6. Simulations of the state proportional controller (10) on the system (1). The motor velocity is changing smoothly and the oscillations are damped. The effect of the underlying PD-motor controller can be seen in the motor position curves.

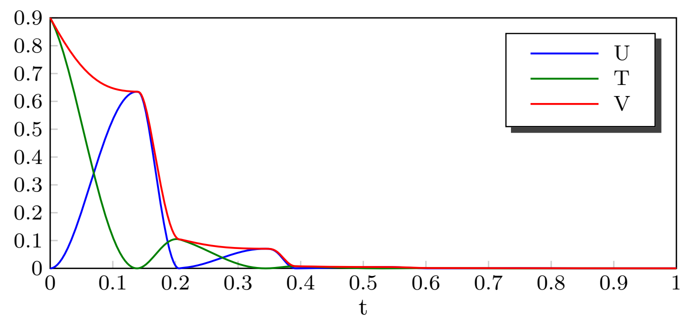

Fig. 7. The potential energy U, the kinetic energy T, and the system energy V. Once, the initial kinetic energy T is transformed to potential energy U, the controller acts to damp the system. After the first oscillation period almost 90% of the energy are removed, and after the second one more than 98%

	Parameters		Init Values
M	1.8 kg	$q(t=0)$	0 rad
B	0.3100 kg	$\dot{q}(0)$	-1.0 rad/s
K	207 N/m	$\theta(0)$	0 rad
K_p	8000 Nm/rad	$\dot{\theta}(0)$	0 rad/s
K_d	200 Nm/rad/s		

The system states are plotted in Fig. 6. The system is disturbed by the initial link side velocity $\dot{q}(0) = -1.0$ rad/s. The controller effectiveness can be clearly followed in the system energy plot Fig. 7. Once, the initial kinetic energy T is transformed to potential energy U, the controller acts to damp the system. After the first oscillation period almost 90% of the energy is removed, and after the second one more than 98%. It is to remark, that the damping used in the simulations is lower than for most practical systems.

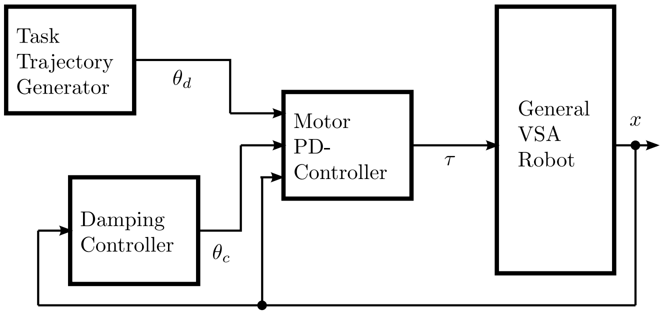

Fig. 8. The velocity command damping controller is used in a cascaded structure with a motor PD controller. The damping controller realizes the damping and state recovery action on a velocity level, where the PD-controller acts on torque level.

2) State Triggered Control: Another solution complying with the damping control law (9) is

$$\boldsymbol{u} = \begin{cases} \underline{\dot{\boldsymbol{\theta}}} & \text{if } (\boldsymbol{\theta} - \boldsymbol{q}) > \boldsymbol{0} \ \& \ \dot{\boldsymbol{q}} \ \geq \boldsymbol{0} \\ \overline{\dot{\boldsymbol{\theta}}} & \text{if } (\boldsymbol{\theta} - \boldsymbol{q}) < \boldsymbol{0} \ \& \ \dot{\boldsymbol{q}} \ \leq \boldsymbol{0} \\ \boldsymbol{0} & \text{else,} \end{cases} \tag{11}$$

where $\underline{\dot{\boldsymbol{\theta}}} < \dot{\boldsymbol{\theta}}_m < \overline{\dot{\boldsymbol{\theta}}}$ are the motor velocity limits, see Section IV-C. Advantages of this controller are that no gains at all have to be tuned and that the system states are only triggering the controller action and are not needed for continuous feedback. The last point may be beneficial if sensor quality (noise, resolution, etc.) is limited.

C. Cascaded structure controller

The velocity control law (9) and some of the subsequent bring back motion laws (14) are providing command trajectories. The trajectories are not open loop, as the system state is fed back to generate these trajectories. Still they are realized by an underlying PD-motor controller in a cascaded structure, as depicted in Fig. 8. To obtain a desired motor position, the velocity signal is integrated

$$\theta_c(t) = \int_0^t u(\tau)\ \mathrm{d}\tau. \tag{12}$$

The separation into a velocity controller and the torque controller requires a two-time-scale-system. Such a system can virtually be split up in two coupled subsystems, one with a faster and one with a slower part (see e.g. [17]). The assumption is considered as mild in the practical case, as the control law does not rely on precise tracking performance. As described by (7), the system energy is reduced in any case when the motor velocity $\dot{\boldsymbol{\theta}}$ is opposing the spring deflection $\boldsymbol{\theta} - \boldsymbol{q}$. Therefore, even if the motor velocity trajectory is not perfectly tracked, as long as the motor velocity has the right sign, the system energy is decreased. For most systems, motor velocity limits $\underline{\dot{\boldsymbol{\theta}}} < \dot{\boldsymbol{\theta}}_m < \overline{\dot{\boldsymbol{\theta}}}$ can be found, such that the motor performance is approximated.

D. Bring back methods

Once the system is brought to a rest the system state is usually different than desired. The task of the bring back method is to re-establish a desired state $\boldsymbol{q} = \boldsymbol{q}_d$. Therefore, several solutions are possible, three presented in the following. They range from state based methods to model based open loop trajectories and damping controllers.

1) An only state based bring back motion generator can be realized by using a so-called leaky integrator instead of the normal one in (12), here written as Laplace transfer function
$$G(s) = \frac{1}{1 + s\ T_c}, \tag{13}$$
where T_c is a time constant. It actually works as low pass filter and ensures that the wrong state resulting from the velocity damping controller is forgotten with time. Resulting, the original desired state is recovered. The stability of this method is again based on the singular perturbation assumption. The stability of linear control methods for slowly varying non-linear systems is well known [18]. Furthermore, our modeling assumptions neglect the existence of mechanical parasitic link and spring damping. In general, these effects can be modeled as energy dissipating terms in (1) and therefore support the action of damping controllers.
This solution is state free but requires tuning and adaptation to the robot properties to ensure performance. Its implementation simplicity and the fact that no model knowledge is needed justifies the application in some systems.
2) A model based method is to use a pre-planned velocity trajectory to bring the system state back to the desired state. Therefore, an open-loop trajectory is designed by a model inversion approach. The motor velocity trajectory is given by
$$\begin{aligned} \boldsymbol{u} = \dot{\boldsymbol{q}}_d + \boldsymbol{k}(\boldsymbol{\varphi})^{-1} \Big(& \dot{\boldsymbol{M}}(\boldsymbol{q}_d)\ddot{\boldsymbol{q}}_d + \boldsymbol{M}(\boldsymbol{q}_d)\boldsymbol{q}_d^{(3)} + \\ & \dot{\boldsymbol{C}}(\boldsymbol{q}_d, \dot{\boldsymbol{q}}_d)\dot{\boldsymbol{q}}_d + \boldsymbol{C}(\boldsymbol{q}_d, \dot{\boldsymbol{q}}_d)\ddot{\boldsymbol{q}}_d + \dot{\boldsymbol{g}}(\boldsymbol{q}_d) \Big) \end{aligned} \tag{14}$$
The trajectory needs to fulfill $\boldsymbol{q}_d(t) \in \mathcal{C}^3$ as to avoid jumps in the motor velocity[2]. A standard trajectory generation method allowing to specify bounds on the start and end position and velocity is provided by a polynomial approach [19].
3) Another model based possibility is to use a passive damping controller. Such a controller normally feedbacks not only the motor velocity and position, but also the link velocity and position. In general, link side feedback to the motor torque is not passive due to its non-collocation property[3]. There exist controllers ensuring the passivity property, however a frequent problem is their limited performance to damp out link oscillations.
In a setup with the velocity damping controller as presented here, the problem of limited performance is

[2]For practical reasons it may be also desirable to avoid discontinuous motor torque.

[3]If a sensor and actuator pair allows to control the instantaneous power between two subsystems, it is collocated [20], [21].

of minor relevance, as most of the energy injected by a disturbance is dissipated by this controller. A subsequent passive damping controller is only damping out residual oscillations and guaranteeing a well damped bring back motion.

V. Controller: Gravity and Multi-DOF

A. Gravity Effects

The considerations until this point did not discuss the influence of gravity, as it occurs in (1). It was assumed that the equilibrium of the controlled robot only depends on the joint elasticity, and such on the potential energy $V(\boldsymbol{x})$. Therefore, the motor and link position coincide there $\boldsymbol{\theta} = \boldsymbol{q}$. In the presence of gravity, the link is deflected from the motor position $\boldsymbol{\theta} \neq \boldsymbol{q}$ due to the garvity forces $\boldsymbol{g}(\boldsymbol{q})$. In [16] it is shown, that for general VSA robots it is always possible to find a motor position $\boldsymbol{\theta}$ such that $\boldsymbol{q}$ can be controlled to a given $\boldsymbol{q}_d$ in the static case. This motor position, resulting in the desire link position at static equilibrium, is denoted $\bar{\boldsymbol{q}}(\boldsymbol{\theta})$. By using $\boldsymbol{q} = \bar{\boldsymbol{q}}(\boldsymbol{\theta})$ in (9)[4] the controller is directly applicable in the presence of gravity.

This result can be intuitively understood as the controller idea relies on the fact that kinetic energy is transferred into potential energy and then parts of the potential energy are dissipated. Gravity has an effect on the energy levels and its equilibrium position. However, what the exact values are is not primarily relevant for the success of the controller.

B. The Multi-Joint Case

The main result in Section IV-A about power dissipation by spring relaxation (9), can be similarly stated in the multi-joint case: Energy can be dissipated from the multi-joint system by a joint wise relaxation of the deflected elastic elements[5]. The same controllers can be used to damp out the oscillations, see Fig. 12. The link inertia and Coriolis/centrifugal matrix $\boldsymbol{M}(\boldsymbol{q}), \boldsymbol{C}(\boldsymbol{q}, \dot{\boldsymbol{q}})\dot{\boldsymbol{q}}$ introduce a coupling between the joints which is not accounted for by the controller. Therefore, the damping performance is somewhat limited, but the goal to damp out the oscillations is eventually achieved. A possible solution for improvement is by designing the controller in a modal coordinate, see e.g. [15]. This is subject to further research.

VI. Experiments

Two sets of experiments with this controller on the DLR Hand Arm System have been conducted. Initially, the robot was configured such that the controller could be tested on a single axis without the effect of gravity.

In a first experiment no damping controller has been activated and the motor has been position controlled. The disturbance resulted in long lasting oscillations of the link side, see Fig 9. Damping experiments have been conducted with both, the state proportional control law Fig. 10 and the state triggered control law Fig. 11. In both cases the oscillations are damped, and the leaky integrator approach re-establishes the desired system state.

Furthermore, experiments on two axes without gravity have been conducted, see Fig. 12. The state triggered control law was used again. Although the energy coupling due to the link inertia and Coriolis/centrifugal effects, the system is well damped.

VII. Discussion

To be able to compare the damping control approach as presented with other controllers, in the following we discuss some of its important properties.

A big advantage of the controller is its independency of a system model. It uses purely state measurements to

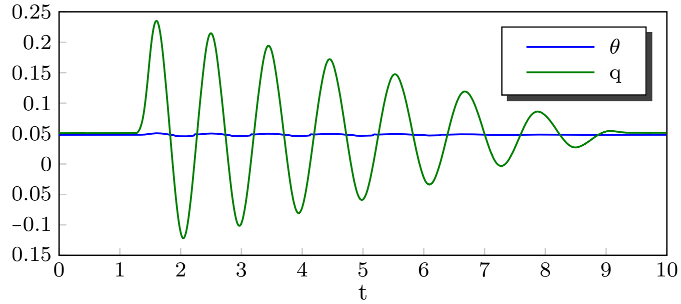

Fig. 9. Reference experiments of the disturbed system, with only position control and q_d = const. After a disturbance, long lasting link oscillations occur.

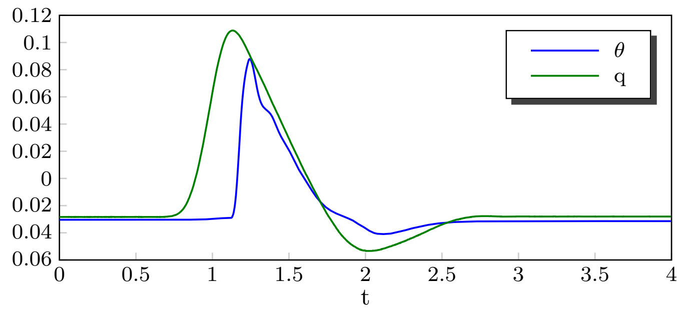

Fig. 10. The link is passively decellerated by the spring, until the state proportional damping controller (10) kicks in and removes potential energy. Afterwards, the system is brought back to the desired state by the leaking integrator bring back method (13).

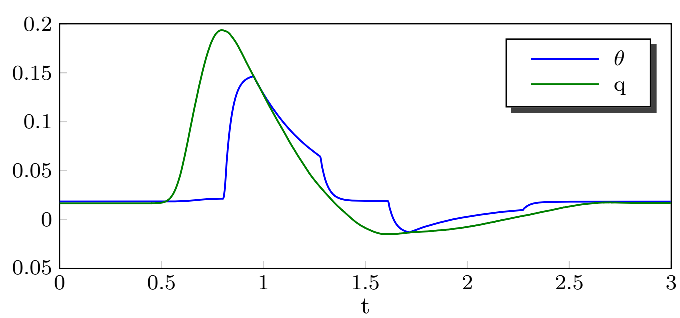

Fig. 11. Similar experiments as in Fig. 10, this time with the state triggered control law (11).

[4]And subsequently also the controll laws (10) and (11).

[5]Please note our preceding comment on coupled (biarticular) joints.

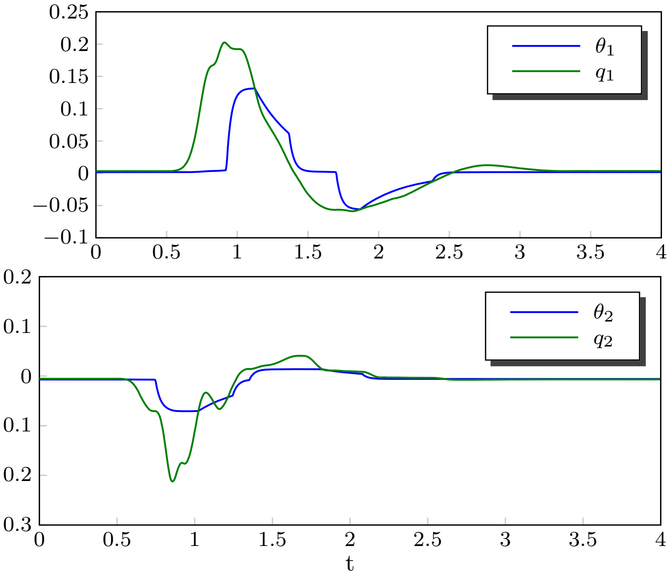

Fig. 12. Experiments on two axes of the DLR Hand Arm System with joint wise application of the damping controller (10). The damping performance is lowered as couplings introduced by the link inertia and Coriolis/centrifugal matrices $\boldsymbol{M}(\boldsymbol{q}), \boldsymbol{C}(\boldsymbol{q}, \dot{\boldsymbol{q}})\dot{\boldsymbol{q}}$ lead to power flow between the joints. Still, after few cycles the links come to rest and the original state can be recovered.

achieve link damping. Even more, the controller reacts in an energetically passive way and thereby stability is ensured. A downside is the possible performance. Model based approaches allow for better damping performance, which is intuitive. This is especially revealed in the multi-DOF case, as the inertia couplings are not accounted for. Still, the damping performance is very good, as the experiments validate.

VSA systems are build to be mechanically tuned to the desired task. Additional control action can distort this natural mechanical reaction. The presented controller aims to preserve the natural robot behaviour for a big portion of the disturbance event: The controller does not intervene the disturbance until a late moment and thereby the natural robot behaviour is responding. This goes in line with the concept of physical embodiment.

Another advantage of the control scheme is its relative independence of state measurements. In most control systems the controller gains are limited by sensor quantization and noise. As with the described controller it is possible to formulate algorithms which are only triggered by state events (single state measurements, see (11)) somewhat a robustness against state signal errors can be achieved.

VIII. Conclusion

In this work we presented a model-free damping controller. It relies on the fact that the joint elasticities decellerate the links, if the motor position is held constant. Thereby, the disturbance kinetic energy is transformed into potential energy. After the link is at rest, the controller relaxes the elastic elements and thereby effectively damps the system. Afterwards, a bring back motion re-establishes the desired system state. The controller shows very good damping performance, is model free and relies only on state measurements, is applicable for multi-joint systems, works also in the gravity case, and exploits the natural dynamics of the robot and therefore supports the physical embodiment idea. The results are validated by experiments on the DLR Hand Arm System.

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