Energy Efficient Actuation with Variable Stiffness Actuators

Ludo C. Visser, Raffaella Carloni and Stefano Stramigioli

***Abstract*— Research effort in the field of variable stiffness actuators is steadily increasing, due to their wide range of possible applications and their advantages. In literature, various control methods have been proposed, solving particular problems in human-robot and robot-environment interaction applications, in which the mechanical compliance introduced by variable stiffness actuators has been shown to be beneficial. In this work, we focus on achieving energy efficient actuation of robotic systems using variable stiffness actuators. In particular, we aim to exploit the energy storing properties of the internal elastic elements.**

I. Introduction

Variable stiffness actuators are a particular class of actuators with the capability of changing the apparent actuator output stiffness independently from the apparent output position. To achieve this, variable stiffness actuators have internally compliant elements, and a number of actuated degrees of freedom that determine how these elements are perceived at the actuator output. By introducing a mechanical compliance to the joints, the motor inertias are decoupled from the robotic system itself, guaranteeing safe interaction with both humans and the environment [1]. However, the mechanical compliance can also be used as a means of storing energy. By properly tuning the apparent output stiffness of the actuator, more energy efficient actuation of periodic motions can be achieved by storing negative work [2].

In achieving energy efficient actuation with variable stiffness actuators, the desired motion should be periodic in nature and the variable stiffness actuator should be efficient in changing the apparent output stiffness. The first condition implies that it is sensible to temporarily store energy, because periodic motions have a energy conserving property. The second condition ensures that using a variable stiffness actuator is a sensible solution.

In this work, we present an overview of our work on modeling variable stiffness actuators, and our efforts in solving the problem of energy efficient actuation.

II. Generalized Behavior of Variable Stiffness Actuators and a Load

The behaviour of a variable stiffness actuator connected to a load can be modeled in a generic way. Let $x = [s\ p\ q\ r]^T$ be the state of the system, where s is the state of the springs, p the momentum of the load, q the configuration of

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The authors are with the Department of Electrical Engineering, Faculty of Electrical Engineering, Mathematics and Computer Science, University of Twente, Enschede, The Netherlands.

e-mail: {l.c.visser,r.carloni,s.stramigioli}@utwente.nl

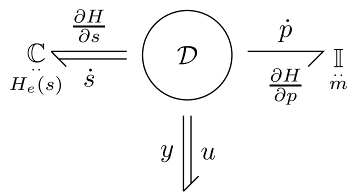

Fig. 1. Generalized model of a variable stiffness actuator with a load - The internal elastic elements are represented by the multidimensional $\mathbb{C}$-element, and the load is represented by the $\mathbb{I}$-element. The internal degrees of freedom are actuated via the control port (u, y).

the internal degrees of freedom, and r the actuator output position. As depicted in Figure 1, the variable stiffness actuator and the load can be modeled in a port-based setting as an input/output port-Hamiltonian system, described by:

$$\begin{bmatrix} \dot{s} \\ \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} 0 & B(q,r) & 0 & 0 \\ -B^T(q,r) & 0 & 0 & -1 \\ 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} \frac{\partial H}{\partial s} \\ \frac{\partial H}{\partial p} \\ \frac{\partial H}{\partial q} \\ \frac{\partial H}{\partial r} \end{bmatrix} + \begin{bmatrix} A(q,r) \\ 0 \\ 1 \\ 0 \end{bmatrix} u$$

$$y = \begin{bmatrix} A^T(q,r) & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \frac{\partial H}{\partial s} \\ \frac{\partial H}{\partial p} \\ \frac{\partial H}{\partial q} \\ \frac{\partial H}{\partial r} \end{bmatrix} \tag{1}$$

where $A(q,r)$ and $B(q,r)$ describe the kinematics of the actuator, and $H(s,p,q,r) = H_e(s) + H_p(p)$ is the Hamiltonian energy function of the system, i.e. the sum of the stored elastic energy and the kinetic energy stored in the mass. The input u corresponds to the rate of change of the configuration variables q, and the output y are the generalized forces generated by them. The apparent output stiffness is defined as:

$$K = \frac{\partial^2 H}{\partial r^2}$$

To capture the behaviour of the load, we can define a change of coordinates $S : \dot{q} \mapsto (\dot{\bar{r}}, \dot{K})$, such that the variable stiffness actuator can be controlled in terms of its equilibrium position $\bar{r}$ and the apparent output stiffness K. Various new control methods, exploiting the properties of variable stiffness actuators, have been proposed in which r follows a certain trajectory by proper control of $\bar{r}$, while at the same time K attains specific values deemed appropriate for the task [3], [4]. Examples include safe human-robot interaction and stable robot-environment interaction, i.e. a mechanical approach to impedance control [5].

The approach we are interested in is to use the internal elastic elements to temporarily store energy during periods of the motions of the actuated joint in which negative work is done. The question then becomes what values $\bar{r}$ and K should attain to achieve this optimally, given a desired motion of the joint. Optimal in this context means that as little energy as possible should be supplied by the controller of the variable stiffness actuator. It should be noted that, in practical realizations, there is a cost associated with changing $\bar{r}$ and K, and therefore that the problem of finding optimal values should be considered in the context of these costs.

Solving this problem consists in two parts: efficiently changing $\bar{r}$ and K, and finding trajectories for $\bar{r}$ and K that are optimal for a given desired trajectory r. In the subsequent sections we cover these two topics.

III. Variable Stiffness Actuation for Energy Efficiency

In previous work, we introduced the notion of energy efficient variable stiffness actuators [6]. In particular, it was shown that, in order to change the apparent output stiffness of a variable stiffness actuator in an energy free way, i.e. without changing the energy stored in the internal compliant elements, the kinematics of the variable stiffness actuator design should satisfy certain properties. It was shown that the class of actuators satisfying these properties is capable of temporarily storing energy internally in the elastic elements, and reusing this energy for actuation. In particular, in [7] we showed that this class of actuators can be controlled so that externally injected energy (e.g. from a disturbance) can be reused for actuation. Figure 2 shows that this new control method indeeds achieves more energy efficient actuation.

IV. Variable Stiffness Actuation for Embodying Desired Behavior

Another approach for energy efficient actuation of periodic motions is to tune the apparent output stiffness to the nature of the desired motion. A clear example is a harmonic oscillation, in which the actuator stiffness can be tuned to the frequency of the oscillation. In [8], it was shown for multi-harmonic reference trajectories, that the joint stiffness can be tuned to a value that minimizes the required actuator torque. It was assumed that the optimal stiffness is a constant value, which results in some natural harmonic motion of the joints, onto which an additional motion is superimposed to achieve the desired joint motion. The optimal stiffness minimizes the torque required to generate the superimposed motion.

However, there is no reason to assume that it is not possible to achieve even higher efficiency when K is allowed to vary around some optimal value, in unison with changes of $\bar{r}$. In particular, considering the aforementioned observation that there is a cost associated with changing both $\bar{r}$ and K, such solutions are worth considering. This problem may be

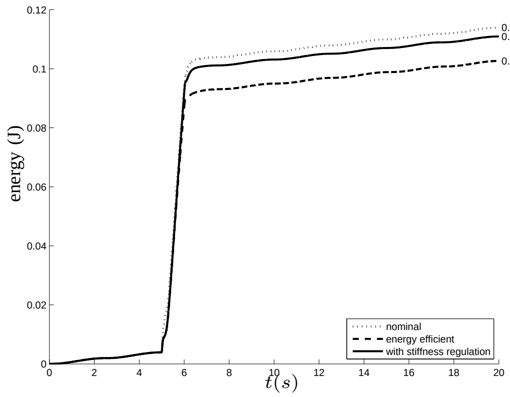

Fig. 2. Energy supplied via the control port - The energy efficient control law clearly achieves a reduction in supplied energy. When stiffness regulation is added, some of the gain in efficiency is lost.

cast into finding a solution that minimizes the criterion

$$J = \int_0^\infty \frac{1}{2}\|\bar{r}^* - \bar{r}\|^2 + \frac{1}{2}\|K^* - K\|^2 \, \mathrm{d}t \qquad (2)$$

where $\bar{r}^*$ and K^* denote a (unknown) optimal value around which $\bar{r}$ and K should vary. Together with the norms $\|\cdot\|$, they define an optimal region in which these values can vary.

V. Conclusions

In this paper, we presented our current results and ongoing efforts on energy efficient actuation with variable stiffness actuators. Ongoing research aims at finding control methods for multi degree of freedom systems. In particular, it is necessary to investigate, given that there is stored energy available, what joint trajectories achieve a desired task so that this energy is maximally reused for actuation. Moreover, in order to realize a controller that embodies a desired behavior, future work will focus on the design of the optimal values for output position and apparent output stiffness.

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