Impedance Control of Series Elastic Actuators Using Acceleration Feedback

Andrea Calanca, Riccardo Muradore and Paolo Fiorini

1 Introduction

More and more robots are designed to help or substitute humans both in daily activities and dangerous scenarios. These robots should be able to cope with humans and with other robots and to move in houses, factories, hospitals and uncertain outdoor terrains. To accomplish these targets robots must be able to move safely in unstructured or uncertain environments and to display relatively high forces with high dynamical precision. Currently a widespread solution is that of using impedance controlled elastic joint robots [7]. While impedance control allows to safely deal with unknown kinematic and dynamic environmental constraints [4], series elastic joints allows impedance controllers to be implemented on high force and high power density motors. This is because accurate impedance control is often implemented relying on a explicit inner force loop [2] and series compliance can dramatically improve explicit force control robustness [1, 8].

The physical interaction with humans and surrounding environments is historically considered an hard challenge in robotics. Solutions are often based on passivity-based (PB) control which is an established control paradigm to provide a high level of stability robustness [3]. In particular in the passive interaction framework passivity of the robot impedance is a sufficient condition to ensure a stable interaction with any passive environment [12], and the human has historically been considered as passive [5].

Several passivity-based force and impedance controllers has been introduced for SEA's. In the seminal works of Pratt and Williamson a passive force controller was introduced, based on positive load acceleration feedback [8]. An interesting aspect of this algorithm is that it not only shows robust stability (passivity) but also robust performance, thanks to the acceleration feedback [1]. It happened that most of subsequent research focused on robust stability while not accounting for robust performance. Vallery et. al. investigated the passivity of SEA control considering a velocity controlled motor. They considered an impedance control schema and

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found that "SEA cannot display a higher pure stiffness than the spring stiffness if passivity is desired". Interestingly this result has been confirmed also with different control architecture. In [9] the impedance is controlled by shaping the admittance at the motor level, aiming at reducing the force control effort for high impedance rendering. Despite not reported in the literature it can be proved that this algorithm leads to the same passivity result i.e. it cannot passively render a stiffness higher than the physical spring stiffness. A similar outcome emerged for the passive impedance control of the the DLR lightweight arm where a parallel force-position architecture has been adopted. Authors implicitly showed that the passivity constraint doesn't allow to overcame the physical transmission stiffness. Further related results state that the physical stiffness limit is even hard to reach. In [10] it is shown that only by using high force control gains the physical stiffness can be approached while in [6] it has been shown that in the case of non collocated force sensor the stiffness limit can be significantly lower than the physical spring stiffness. Also in [11] it has been shown that an impedance controlled SEA cannot passively display a virtual Vogit model dynamics, i.e. the dynamics of a spring in parallel to a damper. In conclusion given the current state of the art there exists no passive algorithm that allows to overcame the physical spring stiffness. Moreover existing passive algorithms cannot display any virtual damping in parallel to the virtual spring.

In this paper we present the first passive algorithm that can overcame such stiffness and damping limitations. The idea is inspired by the seminal work of Pratt and Williamson [8] where they used the above mentioned load acceleration feedback to control the SEA output force. Such acceleration feedback allows the motor to have the same acceleration of the environment thus compensating for load motion and leading to robust performance, i.e. predictable error dynamics. Quite surprising such a performance robustness was not highlighted neither in the original work nor in subsequent publications which focused more on the robust stability issue rather than on robust performance. In fact the effect of the acceleration feedback is to cancel out the load dynamics and we will formally show that leveraging on such load dynamics cancellation we can passively render any passive impedance.

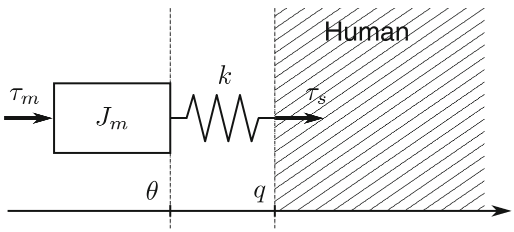

Fig. 1 A model of SEA interacting with an environment

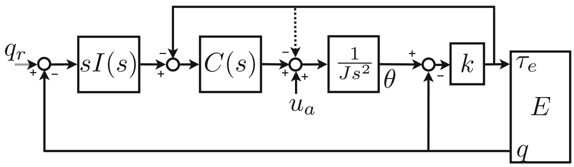

Fig. 2 Impedance control of a SEA. It uses an inner force control loop and an outer position loop to shape the impedance

2 Impedance Control of Series Elastic Actuators

SEA's are usually modeled using the following equations

$$\tau_s = k(\theta - q) \tag{1}$$

$$J_m\ddot{\theta} = \tau_m - \tau_s \tag{2}$$

where, considering the scenario in Fig. 1, τ_s is the spring force (or torque in the case of a rotary joint), θ is the motor position, q is the environment position and τ_m is the motor input force (or torque). The actuator parameters are k and J_m which represent the spring stiffness and the motor inertia respectively. Let us highlight that τ_m is the actuator input while τ_s is actuator output i.e. the force (or torque) exerted on the environment. An impedance control architecture applied to a SEA is shown in Fig. 2, where $u_a = 0$. The force controller $F(s)$ uses the spring deflection feedback and is fed by an outer loop that measures the load position and computes the force reference needed to obtain the desired impedance. As example if we desire a first order impedance, the outer controller should be implemented as

$$sI(s) = d_d s + k_d \tag{3}$$

where d_d and k_d are desired damping and stiffness.

3 Impedance Control Using Acceleration Feedback

In this section we analyze the impedance shaping of a SEA considering the control structure in Fig. 2 where $C(s)$ is a generic stable linear controller, $I(s)$ implements a desired passive impedance and u_a is an auxiliary control output or motor input. This impedance relation can be computed using standard block algebra as

$$-\tau_s = \frac{C(s)I(s) + Js^2 - u_a}{C(s) + \frac{J}{k}s^2 + 1}\, q.$$

If we initially neglect u_a it turns out that the desired impedance relation is approximately satisfied only if $C(s) \gg Js^2$ and $C(s) \gg \frac{J}{k}s^2 + 1$. If this is not the case the actual impedance can be quite far from the desired impedance $I(s)$ an the impedance error is influenced by the environment motion. Interestingly, if we consider the following expression for u_a

$$u_a(t) = \frac{J}{k}\ddot{\tau}_s(t) + \tau_s(t) + J\ddot{q}(t)$$

which includes a positive acceleration feedback, the actual impedance results exactly equal to the desired impedance:

$$-\tau_s = I(s)q.$$

This means *accurate* and *passive* rendering of any passive impedance.

4 Conclusions

The proposed acceleration-based law suggests that embedding the load/environment acceleration in the control law can help to design accurate impedance controllers. Unfortunately the acceleration signal is usually a noisy measure or an approximate estimation. Moreover acceleration overestimation can lead to feedback inversion and instability [8]. For these reasons an acceleration measure or estimation needs to be handled carefully. Also common acceleration processing, such as filtering and amplification, may alter control passivity. In our preliminary experimental results we achieved stable rendering of $3k$, where k is the physical spring stiffness. In our future work we will analyze the passivity of existing impedance controllers and compare them to the acceleration-based approach.

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