Evaluation of Force Feedforward Control for Actuators with Limited Dynamics and Time Delay

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***Abstract*— This paper investigates the effects of time delay and actuator dynamics on the stability and effectiveness of a force feedforward controller for an impedance controlled system, and the applicability of this control strategy to support astronauts during manipulation tasks against the resistance of the gloves of a space suit by means of a hand exoskeleton. To this end, two simulation studies were conducted. To obtain general results, stability was investigated first on the basis of a simple linear system. This first study revealed a highly detrimental effect of time delay on the critical gain factor of the force feedforward controller. Slower actuator dynamics, however, led for the most part to higher stable gain factors. The second simulation study analyzed the applicability of the control approach on an impedance controlled hand exoskeleton. It was shown that the feedforward controller clearly decreases the effort required by the human to move along predefined minimum-jerk trajectories.**

I. Introduction

The force feedforward controller is a well established approach in haptics for reducing the effect of inertia, damping, and friction of a haptic device [1], [2], [3]. It makes use of a force sensor that measures the interaction forces between a human operator and the mechanical system. These forces are scaled and commanded to the actuators in order to support the human movements and hence reduce the disturbing effects of the device.

While haptic devices are usually driven by electric motors that can reach dynamics of several hundreds or thousands Hertz, the situation is different if other actuation technologies come into play. For instance, shape memory alloy (SMA) actuators exhibit dynamic frequencies that are typically orders of magnitudes lower than those of haptic devices [4]. This paper investigates the usability of the force feedforward controller on impedance controlled systems that are driven by such kind of actuators. In particular, it analyses the effect of actuator dynamics and time delay on the stability and effectiveness of a force feedforward controller for an impedance controlled system.

This research is motivated by the work conducted in the European project STAMAS, in which a prototype of an active hand exoskeleton (named HEMS) is developed with the envisaged goal of supporting astronauts during EVAs (Extra Vehicular Activities) [5]. The device is equipped with fingertip sensors to measure the interaction force of the astronaut with the exoskeleton. Due to challenging limitation with regard to weight and available space that arise from the application in outer space, SMA actuators promise to be advantageous compared to electric motors, as they offer high power density at small installation space. However, whether force feedforward control results effective despite of the limited dynamics of SMAs is not clear, and it will be investigated in this paper.

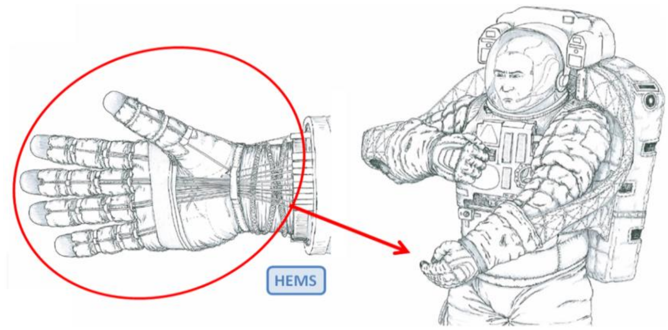

Fig. 1. Concept drawing of the STAMAS hand exoskeleton, also named Hand Exo-Muscular System (HEMS) [5].

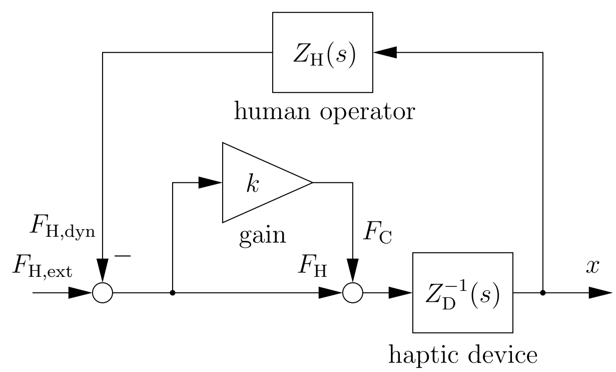

Fig. 2. Continuous-time model of a traditional force feedforward controller for reducing the effects of a haptic device (according to [3]).

This paper presents two simulation studies that investigate (i) the effect of time delay and actuator dynamics on the critical feedforward gain in terms of stability, and (ii) how much this control approach decreases the efforts of the human in the context of the STAMAS hand exoskeleton. It is structured as follows. Sect. II briefly reviews the force feedforward controller and presents the investigated model. Then, Sect. III and Sect. IV describe the two simulation studies and their results. Finally, Sect. V concludes the paper and discusses the impacts of the results.

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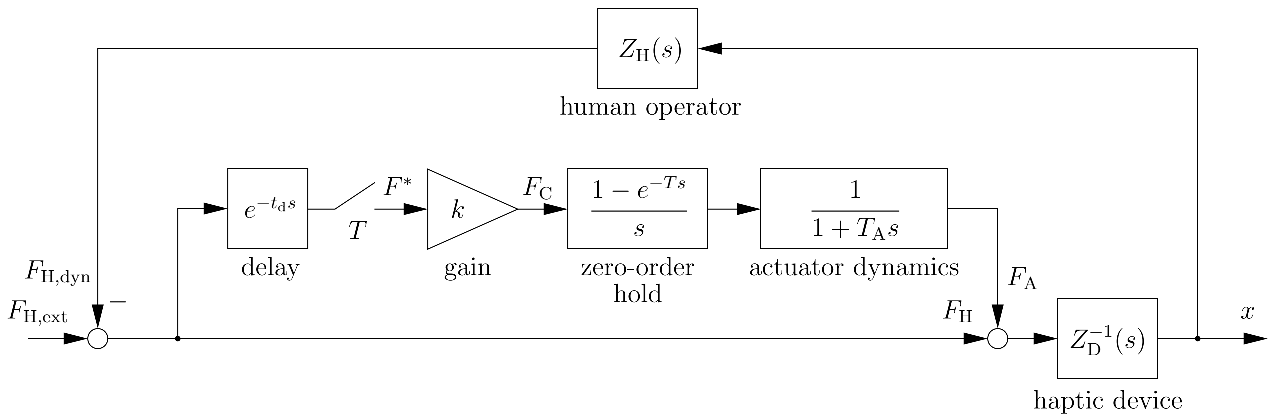


Fig. 3. Considered force feedforward control loop including the effects of discrete-time sampling, actuator dynamics and time delay.

II. Force Feedforward Control

Force feedforward control is a widespread approach to reduce disturbing effects of haptic devices. Its suitability has already been proven on systems such as the DLR lightweight robots [6] and the ARMin rehabilitation exoskeleton [7].

The block diagram of the force feedforward control, using Laplace transfer functions, is depicted in Fig. 2. The user of the haptic device exerts a force $F_{\mathrm{H,ext}}$ to move his own hand and the haptic device. Hence, the total force from the human that acts on the device is this force subtracted by the force due to the dynamics of the human arm, i.e.,

$$F_{\mathrm{H}} = F_{\mathrm{H,ext}} - F_{\mathrm{H,dyn}}. \tag{1}$$

The force feedforward controller scales this force by a gain k resulting in F_{C}. The variable x represents the displacement of the device (and the hand), Z_{H} represents the dynamics of the user's hand, and Z_{D} is the dynamics of the haptic device. As described in [3], the transfer function from force to position is

$$\frac{x}{F_{\mathrm{H,ext}}} = \frac{1}{Z_{\mathrm{H}} + \frac{Z_{\mathrm{D}}}{1+k}}, \tag{2}$$

which means that the equivalent impedance of the haptic device felt by the user is $1+k$ times smaller than the real one.

This control approach has the appealing advantage of not only scaling down the inertia that is felt by the human operator, but also of reducing other disturbing forces that originate from Z_{D}. This property is of crucial importance for the HEMS exoskeleton, which aims at supporting astronauts during EVAs. In such a situation, a major problem is to fight against resistance forces caused by the pressurized glove and its stiff materials [8]. Under the force feedforward controller, astronauts will "feel" less glove resistance and therefore will operate with reduced effort.

Whether or not this approach is effective when time delay and motor dynamics can not be neglected (as it is the case for the HEMS device) needs to be investigated. These effects are considered in the enhanced control loop shown in Fig. 3. The feedforward control approach is represented again by a gain k that scales the forces measured by fingertip sensors of the HEMS device. Delays in the feedforward branch are summarized by t_{d}. It represents the communication delays between sensors, embedded electronics, and actuators, but also the delay that may arise by the thermal actuation principle of the SMAs.

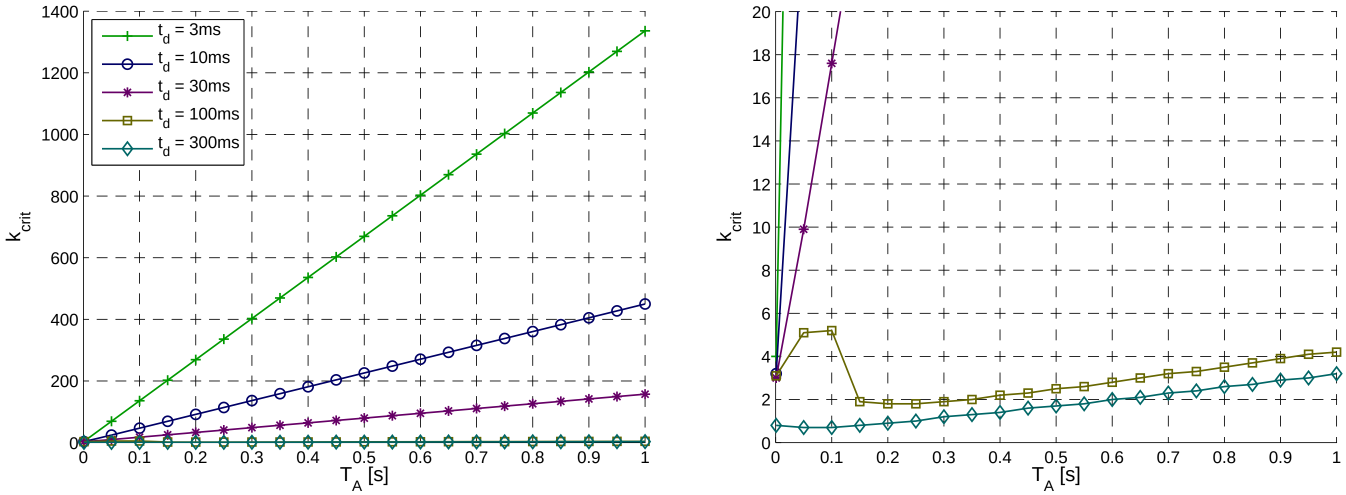
TABLE I
Parameter values of the first simulation.

parameter	symbol	value
sampling rate	T	$0.001\,\mathrm{s}$
device mass	m_{D}	$0.1\,\mathrm{kg}$
device damping	b_{D}	$0.2\,\mathrm{Ns/m}$
human mass	m_{H}	$0.05\,\mathrm{kg}$
human damping	b_{H}	$0.25\,\mathrm{Ns/m}$
human stiffness	k_{H}	$5\,\mathrm{N/m}$

The actuator dynamics are represented by a first order low-pass element with actuator time constant T_{A}. Thus, from the control point of view, the dynamics are equivalent to force filtering [3]. In other words, the results of this paper hold also for systems that include force filtering instead of actuator dynamics.

III. Simulation 1: Effects of Actuator Dynamics and Time Delay on the Critical Gain Factor

The first simulation study investigates the effect of time delay t_{d} and actuator dynamics T_A on the basis of a linear control system. The device is modeled as a damped mass, and the human operator as a mass-spring-damper system. Although these models are approximations, they are often used for analyzing the stability of dynamical systems in which a human operator is involved [9]. The parameter values for the device are $m_{\mathrm{D}} = 0.1\,\mathrm{kg}$ and $b_{\mathrm{D}} = 0.2\,\mathrm{Ns/m}$, and for the human $m_{\mathrm{H}} = 0.05\,\mathrm{kg}$, $k_{\mathrm{H}} = 5\,\mathrm{N/m}$, and $b_{\mathrm{H}} = 0.25\,\mathrm{Ns/m}$. The sampling period is assumed to be constant at $T = 0.001\,\mathrm{s}$, which corresponds to the typical sampling rate in haptics [10]. Although the total delay t_{d} may be small in the final device, relatively high numerical values are considered in the first study in order to reveal the importance of keeping delays small.



(a) full view (b) close-up view

Fig. 4. The influence of time delay t_d and actuator dynamics T_A on the critical feedforward gain k_{crit}. The right plot shows a close-up view for small gains in order to illustrate the nonlinear dependency that occur for long delays.

Fig. 4 shows the simulation results and reveals a clear dependency of the critical feedforward gain k_{crit} on the delay and the actuator dynamics. As it may be expected, the time delay drastically compromises stability, and hence reduces the maximum stable gain k_{crit}. However, the situation is different for the actuator dynamics. A slower dynamics is nearly linearly contributing to stability. Thus, for instance, an extremely slow dynamics of $T_A = 1\,\text{s}$ extends the stable range of feedforward gains up to $k_{\text{crit}} = 1336$, as it can be seen by the uppermost curve, i.e., for $t_d = 3\,\text{ms}$. It is important to note that with such slow actuator dynamics desired reduction of Z_{D} by $k+1$ can not be reached, in general. Rather, only slow dynamics are effectively reduced, whereas quick changes may not be followed by the actuators.

Interestingly, the relation between the critical gain k_{crit} and the actuator time constant T_A becomes nonlinear for large delays of more than $t_d \geq 100\,\text{ms}$ (see Fig. 4(b)). The result is that the critical feedforward gain k_{crit} reduces to small values of around 2 for $t_d = 100\,\text{ms}$ and for slow dynamics of $T_A \geq 0.15\,\text{s}$.

To sum up, the envisaged control approach of force feedforward compensation is also working stably for actuators that are affected by dynamics and delay. However, particular importance must be given to keeping delays small, as they directly compromise the beneficial effects of the feedforward approach. For long delays of more than $300\,\text{ms}$ the dependency between stability and actuator dynamics is even nonlinear.

IV. Simulation 2: Reduction of the Effective Glove Impedance

In order to investigate the effectiveness of the force feedforward controller for an actuated space glove, we have prepared a dynamic simulation model. The basic functionalities of the simulator comprise finger dynamics, forces exerted by the astronaut, glove resistance, and actuator dynamics. Each finger is modeled as a point mass that rotates around a pivot point; the distance between these two points represents the length l of the finger. Rotations are determined by the total torque τ_{total} applied at the pivot point. This total torque can be broken down into three contributions: the torque applied by the astronaut τ_{H}, the one produced by the SMA actuators τ_{A}, and the resistance of the glove τ_{D}:

TABLE II

Parameter values of the second simulation.

parameter	symbol	value
time delay	t_d	$0.003\,\text{s}$
duration of motion	D	$1\,\text{s}$
glove resting state	ϑ_{rest}	$[20, 20, 20, 20, 20]$ deg
initial position trajectory 1	—	$[20, 20, 20, 20, 20]$ deg
initial position trajectory 2	—	$[0, 0, 0, 0, 0]$ deg
glove stiffness	k_{D}	$0.026\,\text{Nm/deg}$
critical gain	k_{crit}	$0.45\,\text{m}$
finger length	l	$0.08\,\text{m}$

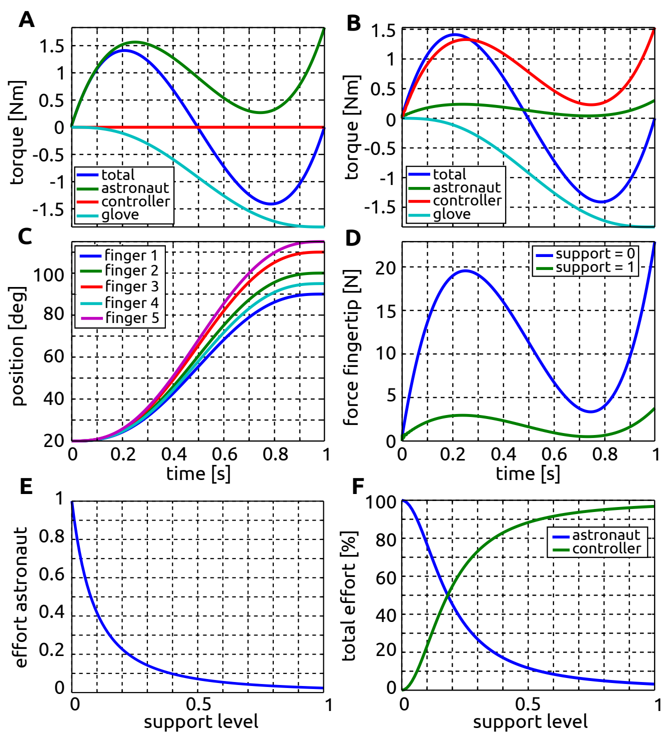
$$\tau_{\text{total}} = \tau_{\text{H}} + \tau_{\text{A}} + \tau_{\text{D}} \tag{3}$$

The torque τ_{H} is translated into the force at the fingertip by means of the lever arm l as $F_{\text{H}} = \tau_{\text{H}}/l$. Since pressure sensors are placed on one side of the fingertips, they can only measure forces that have the same direction of finger motions. Thus, F_{H} is constrained to be non-negative.

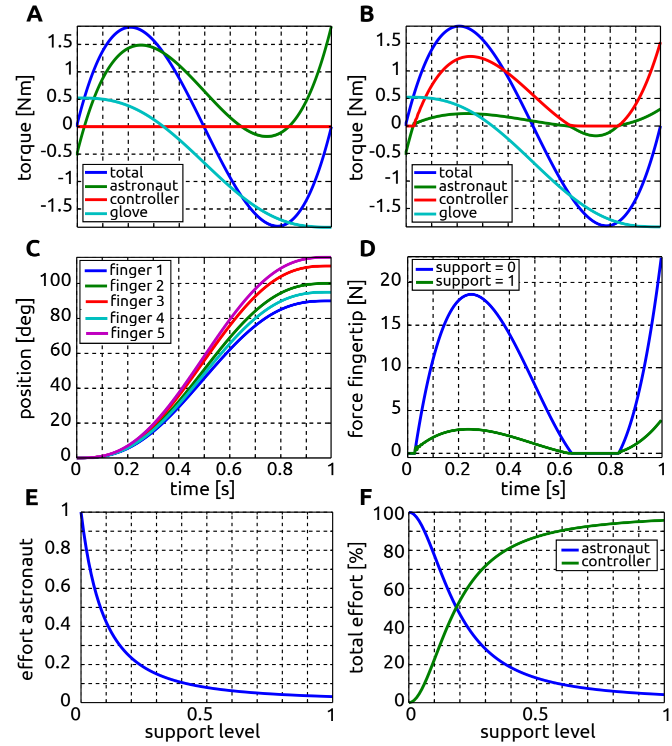
The glove is modeled as a rotational linear spring with stiffness k_{D}. Thus, τ_{D} is proportional to the difference between the current angular position ϑ of the fingers and the resting position of the glove ϑ_{rest}, resulting in the torque

$$\tau_{\text{D}} = -k_{\text{D}}(\vartheta - \vartheta_{\text{rest}}). \tag{4}$$

Actuators are implemented as first order low-pass dynamics. Their inputs are the signals provided by the force feedforward controller, and their outputs represent the forces exerted by the SMAs to the fingers, leading to the torque τ_{A}. The output of the controller is computed as described in



(a) trajectory 1: starts at the resting state



(b) trajectory 2: starts below the resting state

Fig. 5. Required torque and effort contributions to perform the minimum jerk trajectories (C) with minimal (A) and maximal (B) support level, and corresponding forces measured at the fingertip sensors (D). The astronaut effort decreases by increasing the support level of the controller (E). Similarly, the percentage of controller effort with respect to total effort increases with the support level (F).

Sect. II, by multiplying the force readings of the fingertip pressure sensors by the gain $k = \mu \cdot k_{\text{crit}}$, where the support level μ is a scalar between 0 (i.e., no support) and 1 (i.e., maximal support that guarantees a stable controller). While this simulator provides only rough models of SMAs and fingers, it allows us to investigate the effectiveness of the controller, without introducing the complexity of a more realistic model.

In this section, we aim at showing how the contribution of the astronaut τ_{H} reduces by increasing the gain of the controller k, for a given desired kinematic trajectory of the fingers $\vartheta_{\text{des}}(t)$. From the mass-matrix of the fingers, it is possible to compute the total desired torque $\tau_{\text{total}}(t)$ that corresponds to $\vartheta_{\text{des}}(t)$. Thus, the astronaut contribution τ_{H} can be trivially obtained from (3).

The simulation parameters that we have used for this analysis are summarized in Table II. Simulations were performed for two desired minimum-jerk trajectories. Fig. 5(a)C depicts the first one, where the initial positions of the fingers correspond to the resting state of the glove. Fig. 5(a)A-B show the torque contributions for $\mu = 0$ and $\mu = 1$ respectively. It is easy to note that a high support level ($\mu = 1$) leads to an increase of the controller contribution and a decrease of astronaut contribution. Since for this trajectory the astronaut contribution is always positive, the forces measured by the fingertip sensors are always different than zero (see Fig. 5(a)D).

In order to systematically assess the impact of support level on torque contributions, we have defined a measurement of effort as the time integral of the squared torque, i.e.,

$$\eta = \int_0^D \tau^2(t)dt \tag{5}$$

where D is the duration of motion (see Table II). Fig. 5(a)E-F shows that the normalized effort of the astronaut decreases as a function of the support level. Similarly, the relative contributions of astronaut and controller to total effort (defined as $\eta_{\text{H}} + \eta_{\text{A}}$) decreases and increases respectively by varying the support level from its minimum to its maximum. For $\mu = 1$ the controller contributes more than 95% of the total effort to move the fingers along the desired trajectory against the resistance of the glove.

The second desired minimum-jerk trajectory, and corresponding torque contributions, are depicted in Fig. 5(b). It can be noticed that, at the beginning of the motion, the glove contributes positively to the desired torque, and that the astronaut needs to compensate this disturbance by applying a negative torque that allows him/her to track the desired trajectory. Since the fingertip sensors can only detect pressures (i.e., positive forces F), they measure zero values while the astronaut applies negative torques (see Fig. 5(b)D).

As a result, in those intervals, the controller does not contribute any torque (see Fig. 5(b)B). Nevertheless, as long as the required torque contribution of the astronaut is not negative during the whole motion, high support levels lead to reduced astronaut effort (Fig. 5(b)E-F).

V. Conclusions

The present document investigated the force feedforward control approach and tested its suitability for the STAMAS hand exoskeleton. We have shown that the maximum gain that renders the feedforward controller stable (i.e., critical gain) is highly dependent on time delays and actuator dynamics. In detail, time delays deteriorate stability, while slow actuator dynamics led for the most part to higher critical gains. We also showed that the force feedforward controller used on the STAMAS hand exoskeleton reduces substantially the effort required by the astronaut. Thus, this controller promises to be of great benefit in assisting astronauts during EVAs.

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