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A time-domain vibration observer and controller for physical human-robot interaction

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ABSTRACT

This paper presents a time-domain vibration observer and controller for physical Human-Robot Interaction (pHRI). The proposed observer/controller aims at reducing or eliminating vibrations that may occur in stiff interactions. The vibration observer algorithm first detects minima and maxima of a given signal with robustness in regards to noise. Based on these extrema, a vibration index is computed and then used by an adaptive controller to adjust the control gains in order to reduce vibrations. The controller is activated only when the amplitude of the vibrations exceeds a given threshold and thus it does not influence the performance in normal operation. Also, the observer does not require a model and can analyze a wide time frame with only a few computations. Finally, the algorithm is implemented on two different prototypes that use an admittance controller.

1. Introduction

Although robots have been used for several decades, direct physical interactions between robots and humans are rare, for obvious safety reasons. The most evident means of ensuring safety is to segregate robots and human beings thereby leading to robots designed and programmed to work in a closed cell. However, in several applications, it is desirable to exploit the force capabilities of robots by directly combining them with the skills of a human being, hence leading to human augmentation. The main challenge for human augmentation systems is to perceive their environment and the human intentions and to respond to them adequately, intuitively and safely.

Physical human-robot interaction (pHRI) is emerging in many applications. In manufacturing, robots are used to work closely with operators in the same workspace. This includes for instance assistive devices [1,2] and new commercial robots such as the Kuka LWR 3 [3], Baxter [4], Universal Robots [5] and several more. In healthcare, a popular example is the da Vinci robotic surgical system used to assist surgeons. In this cooperation context between humans and robotic devices, the human role can be to lead the task or to follow the robot lead [6]. In [7], an algorithm was developed to automatically adjust the robot role between the leader and the follower depending on inferences of the interaction with the human operator.

The interaction with these devices must be safe and intuitive and a major concern to achieve this is related to stability and vibration issues. While the issue of stability is practically resolved in a large number of applications, vibrations remain a challenge, especially with stiff interactions.

It is well-known that the interaction between two different systems can generate vibrations in a closed-loop feedback scheme. This is especially true when the interaction is physically stiff. The source of the stiffness can be an object in a virtual world or in the real world (for instance the person interacting with the device as studied in [8] where the hand impedance of several operators was measured). Vibration problems arise from different sources, namely: limited bandwidth, latency or delay, discontinuities in the feedback loop or in the reference, modelling inaccuracies, mechanical friction, noise, sensor resolution and others.

This paper is structured as follows. First, a review of the state of the art in technologies for reducing vibration and analyzing system stability is presented. The primary contribution of this paper, namely, a non-linear algorithm for measuring and eliminating vibrations coming from direct physical interaction is presented with the aim of improving operator safety. This algorithm is referred to in the following as an active time-domain vibration observer and controller. We then describe the method used to extract a vibration index based on minima and maxima (extrema) from a given

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signal with robustness in regards to noise. This index is then used by an adaptive controller in order to reduce or eliminate the vibrations. The observer does not require a model and can analyze a wide time frame with only a few computations. Also, the controller is activated only when the amplitude of the vibrations exceeds a given threshold (both in frequency and amplitude) and thus it does not influence the performance in normal operation. Finally, the implementation of the algorithm on two different prototypes is described in order to demonstrate its performance.

2. Literature review

Stability and vibration issues in haptics and pHRI have received considerable attention in the literature. A popular method to reduce vibrations is to use an artificial impedance or admittance link between the haptic display and a virtual world. The objective is to decouple the haptic control and the model of the virtual environment [9]. This virtual coupling is always used and reduces the task performance. Another approach is to model the system and adaptively adjust the controller parameters with the help of the sensors related to the human movement in order to avoid vibrations. The parameters can be adjusted using the well-known Routh-Hurwitz criterion, root-locus, Nyquist, Lyapunov, μ-analysis, or other similar techniques [10].

A very popular method is to use the energy transferred in the system with concepts such as time domain passivity [11,12] or absolute passivity [13]. Passivity theory in the time domain has been used in many applications such as bilateral control of teleoperators under time-varying communication delays [14,15] and for the control of haptic interfaces [16]. In the latter case, virtual damping parameters are used to reduce vibrations. These passivity observer and controller (PO/PC) are only activated when required and thus they minimally degrade the performance [12]. Passivity theory is also applied in the frequency domain to adjust impedance filter parameters [17] and to define passivity-equivalent systems [18]. Another frequency-domain stability observer is proposed in [19]. One of the challenges of frequency-domain methods is the computational burden, especially with large data sets and real-time control constraints.

3. Vibration observer

This section explains the vibration observer/controller algorithm. The general principle is first presented, followed by the description of a wide time window and a narrow time window. Finally, the vibration index is defined. Fig. 1 presents the general vibration observer-controller scheme while Fig. 2 presents the structure of the vibration observer. A video (see Electronic Annex 1 in the online version of this article) accompanying this paper summarizes the algorithms and shows experimental results [The video was placed on Youtube for the Review only].

3.1. Proposed algorithm

In order to assess the vibrations in a signal at a given time t_0, the last discrete w points of the signal are considered. In terms of time, this is equivalent to the interval $t \in [(t_0 - T_w), t_0]$, referred to as the *wide time window*. In the context of human-robot interaction, the signal whose vibrations are analyzed can be the measured velocity, the desired velocity or the interaction force. The first step is to find all the minima and maxima of the signal in the wide time window. This is done by using a *narrow time window* technique.

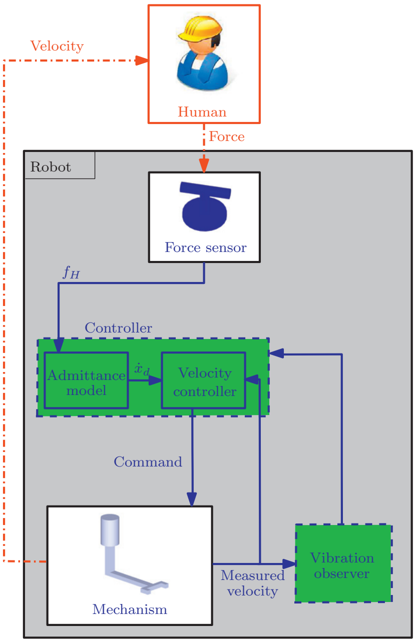

Fig. 1. General structure of the vibration observer-controller: r is the reference, u is the control output, y_2 is the output and y_1 is the signal considered for the vibration observer.

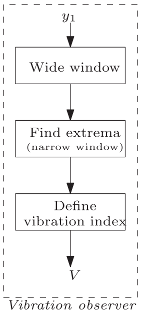

Fig. 2. Structure of the vibration observer: y_1 is the observer input and V is the observer output.

Based on these extrema, a vibration index is computed and is then used by an adaptive controller to adjust control gains thus reducing vibrations.

3.2. Wide time window

The duration of the wide time window, T_w, is a very important design parameter. Since the vibration index is based on the detection of minima and maxima, one should have

$$T_w > \frac{1}{f_l} \tag{1}$$

where f_l is the lowest frequency to be accounted for in the vibration index. At a given time, only the vibrations inside the wide time window are considered. Fig. 3 illustrates the concept of wide time window. The width of the wide time window may be adjusted depending on the applications. The authors suggest a minimum time frame of

$$T_w \simeq \frac{3}{f_l}. \tag{2}$$

3.3. Narrow time window

In order to characterize the vibration level, all the signal minima and maxima within a wide time window are identified. To this