A smooth approximation of mobile platform displacement for Mobile Haptic Interfaces

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Abstract

One of most interesting aspects in haptic research deals with the extension of application workspace, thus allowing haptic simulation within large virtual environments. Several devices have been realized that allow this kind of interaction, in particular our interest focuses on mobile haptic interfaces, realized by combining classic grounded haptic devices with mobile platforms. While grounded haptic interfaces feature fast sampling rate and finest quantization, mobile haptic interfaces are multirate devices where the displacement sampling of mobile platform may affect the quality of haptic rendering. In this paper we introduce a simple smoothing algorithm that allows to approximate a slow-rate and rough-quantized sampled signal representing mobile robot displacement with a fast rate and smooth signal. Evaluation experiments confirmed that the proposed algorithm allows to preserve a good quality of haptic rendering.

1. Introduction

One of the factors affecting the realism of Virtual Reality simulations is the limited workspace that common haptic devices can provide to users. Workspace dimensions strictly depend on device mechanical structure and are often limited to a few cube centimeters. In recent times various haptic devices featuring larger workspace have been proposed (see for instance [4, 5]). These, as well as most standard haptic devices, however, share two main traits: they are grounded and they have limited workspace. This can be a limitation in cases where users need to interact with large virtual environments while navigating inside of them. For example, force feedback have been employed to educate senso-motor abilities of disabled people [1], to train the visually impaired in performing daily-life tasks [2], and even to train blind subjects in spatial orientation and wayfinding inside large environments [3]. For this purpose, it is required to create haptically enabled virtual environments with large extensions which allow also user's navigation.

Mobile Haptic Interfaces have been introduced in [6] . This system is realized by combining a common impedance haptic device (HD) with a mobile platform (MP) (see Fig. 1): the former provides dynamical interaction with virtual objects, the latter allows user's navigation inside wide virtual environments. MHIs

Figure 1: A prototype MHI combining an Omega Haptic Device with a Nomad XR4000 mobile platform.

have some features that set them apart from standard haptic devices. For example, a MHI always features some level of kinematic redundancy and it has dynamical limitations depending on technical specifications of both devices [7]. Moreover the haptic interface and the mobile robot are respectively force controlled and position (velocity) controlled systems, and they may feature different sampling rates and amplitude quantizations. Therefore, in general, a multirate force/position (force/velocity) control algorithm is required [8] to achieve realistic haptic interaction inside large virtual environments. Besides, if an absolute localization system is not available, the simplest way to estimate the global end-effector displacement is the compo-

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sition of relative measurements provided by both haptic device and mobile platform. However, the localization accuracy provided by the mobile platform may affect the quality of the haptic rendering [6]. Problems in haptic rendering with MHIs are mainly due to slow sampling rate and rough quantization of the signal generated by the odometry of the mobile robot, which reflect also on end-effector global localization, thus leading to a possible detriment of the realism in virtual interaction. To solve this problem we propose a new algorithm to refine the estimation of the end-effector displacement, thus allowing to preserve a good level of realism without using expensive absolute localization systems.

Finally, a perceptual experiment has been carried out in order to empirically evaluate the usefulness of the proposed algorithm.

The paper is structured as follows. In Section 2, the dynamical model of a MHI is presented; Section 3 introduces the proposed algorithm; finally in Section 4 the experimental validation is described and discussed.

2. Dynamical model of an impedance-type MHI

For the sake of clarity, in this section we will show the control scheme of a MHI featuring only two redundant DoFs, i.e. the system can move and render forces along the single straight direction x as shown in Fig. 2.

Let us consider a base reference frame Σ_W which is attached to the world. In the scheme of Fig. 2, x_E represents the position of the end-effector with respect to Σ_W; K_{ve} and B_{ve} are respectively the stiffness and the damping of virtual environment local model.

Let's make the assumption that the platform is position controlled. The basic idea is to make the MP track the motion of the operator, thus always driving the HD end-effector towards the center of its workspace [6, 8]. Hence x_M represents the position of the mobile platform with respect to Σ_W. Furthermore, let Σ_M be a mobile reference frame which is attached to the haptic device base: x_H represents the position of the end-effector with respect to Σ_M, as well as the platform tracking error.

Since MP and HD are independent devices, they may feature different sampling times, thus a MHI is generally a multi-rate device. Let T_H and δ_H be respectively the sampling time and the quantization of HD, while T_M and δ_M are the sampling time and the quantization of MP. Generally $T_M > T_H$ and $\delta_M > \delta_H$, thus while the HD hardware provides fast rate and high accuracy in sampling the position of end-effector, MP may feature slow rate and rough positional accuracy. The Fig. 3 shows an example of experimental data acquired using

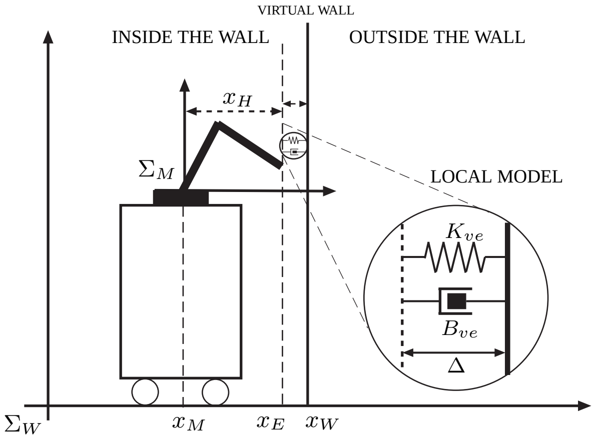

Figure 2: Scheme of a system for haptic interaction between user and virtual environment using a MHI. x_H: haptic device displacement w.r.t. Σ_M. x_M: mobile platform displacement w.r.t. Σ_W. x_W: virtual world position w.r.t. Σ_W. Δ: virtual penetration. K_{ve} and B_{ve}: stiffness and damping of virtual wall local model

the prototype of Fig. 1, realized combining the holonomic platform Nomad XR4000 and an the Omega Haptic Device. $\hat{x}_H$ (dotted line) is the displacement of the haptic probe w.r.t. Σ_M; $\hat{x}_M$ (dashed line) is the displacement of the mobile platform w.r.t. Σ_W; $\hat{x}_E$ (solid line) represents the position of the haptic probe w.r.t. Σ_W and it is the sum of $\hat{x}_H$ and $\hat{x}_M$. While $\hat{x}_H$ is di-

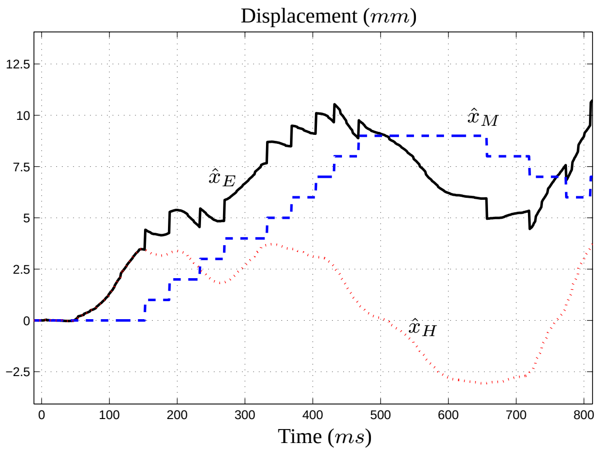

Figure 3: An example of measured signals for the MHI prototype of Fig. 1: $\hat{x}_M$ (dashed line), $\hat{x}_H$ (dotted line), and their sum $\hat{x}_E$ (solid line).

rectly sampled with time $T_H = 0.001s$ and quantization $\delta_H = 0.01mm$, $\hat{x}_M$ is generated by the Nomad odometry at sampling time $T_M = 0.01s$ and quantization $\delta_M = 1mm$, and then resampled in the haptic servo-loop at time T_H. However, being $T_M > T_H$, $\hat{x}_M$ is constant during the time interval between two different odometry measures. On the other hand, in the time instants in which odometry provides a measure different from the previous one, $\hat{x}_M$ exhibits a remarkable amplitude steps, and since $\delta_M >> \delta_H$, these steps propagate also to $\hat{x}_E$.

Since the reaction force is computed relying on $\hat{x}_E$, this phenomenon caused by quantization of $\hat{x}_M$ reflects also to force rendering, and this may deteriorate the realism of the haptic interaction with virtual rigid bodies.

3. Smoothing MP localization signal

The solution proposed in this work consists of computing a smooth signal y_M which approximates the oversampled signal $\hat{x}_M$, thus a smoother estimation of the global end-effector displacement can be obtained as:

$$\hat{x}_E = \hat{x}_H + y_M. \qquad (1)$$

Let be $\hat{x}_M(i)$ the MP displacement sampled at time instant iT_H. The signal y_M is defined as:

$$\mathcal{F} \begin{cases} y_M(i+1) = y_M(i) + K\Delta x(i) \\ \Delta x(i) = [\hat{x}_M(i) - y_M(i)] \\ y_M(0) = 0 \end{cases} \qquad (2)$$

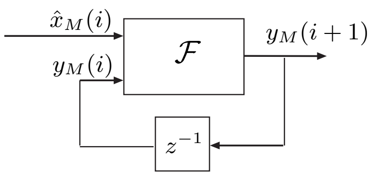

Figure 4: Block scheme of the closed-loop smoother

In other terms, at each time instant iT_H, y_M is updated such that the approximation error $\Delta x(i)$ tends to become zero. The factor K plays a key role in this algorithm: it bounds the maximum difference between two following samples of y_M, but it should also guarantee that the approximation error can be always compensated. Hence, given

$$m = \left\lfloor \frac{T_M}{T_H} \right\rfloor,$$

we want y_M to smoothly track the current MP odometry measure taking m steps. To this purpose, the free state evolution of the discrete-time system (2) has been studied starting from the initial condition $V_M T_M$, which corresponds to the maximum approximation error occurring while the MHI moves at its maximum allowed translational velocity.

Note that, since (2) features one-dimensional state y_M, it can only asymptotically tend to zero, thus K can be determined such that:

$$y_M(m) = \delta_H$$

Therefore, by straightforward computation, we have:

$$y_M(m) = (1-K)^m V_M T_M = \delta_H,$$

that yields the final formula to compute K:

$$K = 1 - \left(\frac{\delta_H}{V_M T_M}\right)^{\frac{1}{m}} \qquad (3)$$

According to the relationship (3), y_M smoothly approximates MP displacements with a tolerable error δ_H, which is comparable with HD quantization error.

4. Experiments and discussion

In order to empirically evaluate the usefulness of the proposed algorithm, we designed an experiment aiming to compare the maximum stiffness that can be correctly rendered by the MHI both with and without smoothing algorithm, using the prototype MHI depicted in Fig. 1.

30 values of stiffness K_{ve}, ranging from 0.3 to $1.5\frac{N}{mm}$, where randomly displayed for 3 seconds both with and without smoothing algorithm. Each subject was asked to report every annoying effect such as vibrations during a virtual contact by pressing end-effector button. Totally 20 subjects participated to the experiment. Table 1 reports the values of the implemented parameters. The parameter K has been computed using the relationship (3). For each user, we considered the stiffness threshold K_{ve} which did not cause annoying effects, both with and without smoothing. Globally, the averages of individual thresholds have been computed, and results are shown in Table 2.

HD SAMPLING TIME	$T_H = 0.001s$
MP SAMPLING TIME	$T_M = 0.01s$
MP MAXIMUM VELOCITY	$V_M = 0.4\frac{m}{s}$
SMOOTHING PARAMETER	$K = 0.45$

Table 1: Parameters implemented in experimental application

STIFFNESS THRESHOLDS	
WITHOUT SMOOTHING: 0.525 ± 0.008	WITH SMOOTHING: 0.863 ± 0.010

Table 2: Experimental results: average stiffness thresholds which save the realism of haptic interaction using a MHI with and without smoothing algorithm.

The experiments confirmed that the proposed smoothing algorithm allows to improve the quality of haptic rendering, increasing the maximum virtual stiffness that can be correctly rendered to the user.

Summarizing, the proposed smoothing technique has the following main advantages: it allows to improve the quality of the haptic rendering using a MHI; it is very simple and requires a minimum computational load; the procedure is general, thus it can be applied with any haptic device and any mobile platform.

On the other hand this algorithm introduces an error on the MP position estimation. however, the maximum error that this algorithm can introduce is $V_M T_M$, occurring while MHI is moving at the maximum allowed velocity. This bound however, is in general negligible: for example, in our experimental setup it is $V_M T_M = 4mm$.

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