Dental Simulator with Increased Z-width of Haptic Rendering

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Abstract. We demonstrate a dental simulator with haptic feedback which can render stiff virtual objects (i.e., tooth) with commercially available haptic devices. In particular, we adopt the passivity-based real-time simulation [4], virtual coupling with passive decomposition [3], and momentum-based disturbance observer [2]. Our dental simulator demonstrates that the proposed method can increase Z-width of haptic renderings significantly while maintaining stability.

Keywords: passive midpoint integrator · passive decomposition · momentum-based disturbance observer · Z-width · dental simulator

1 Introduction

Virtual reality dental training simulators with haptic feedback has gained growing attention in the past decade. Such simulators require to simulate stable interactions with very stiff virtual tooth, of which the quality can be assessed using *Z-width*. Z-width is the range of achievable impedances which has upper limits [1]. Dental simulators require large Z-width since it implies they can desirably render stiffer virtual tooth, resulting in *better* quality of haptic renderings.

Meanwhile, the maximum Z-width can be estimated, practically, from the maximum stiffness in static contact, determined by the stiffness of *spring-damper virtual coupling* and virtual objects. Here, spring-damper virtual coupling is the most widely used technique for connecting haptic device and virtual proxy, in which feedback control uses device-proxy coordination error. Hence, larger stiffness gain is required to increase Z-width; however, it is upper bounded since passivity is more easily violated with larger stiffness [3]. In addition, because coordination error displays reduced Z-width, zero coordination error is required; however, such coordination error is inevitable and necessitated in virtual coupling.

Nevertheless, to increase Z-width while preserving passivity, we adopt passive midpoint integrator (PMI), proposed and adopted for haptic renderings in [4], which can render large stiffness while ensuring stability. In addition, we extend the framework of combining virtual coupling and passive decomposition, proposed in [3], to eliminate coordination error to further increase Z-width.

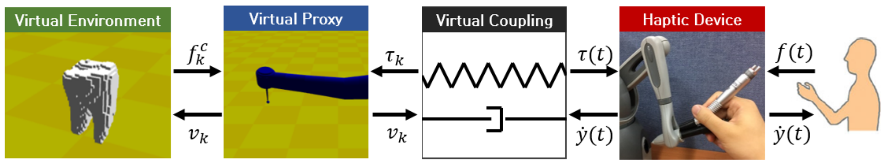

Fig. 1. Diagram of haptic interaction, where a human user interacts with the virtual environment via haptic device, virtual coupling and virtual proxy.

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To maintain stability even with large stiffness, we employ passive midpoint integrator (PMI) [4] for the virtual coupling and virtual objects. Because PMI has a superior energy-conserving property by directly enforcing passivity in the discrete-time domain, the maximum viable stiffness can be significantly increased. System for rigid body can be written by

$$M\frac{V_{k+1}-V_k}{T_k}+B\hat{V}_k=F_k$$
$$X_{k+1}=X_k+\hat{V}_kT_k$$

where, $\hat{V}_k:=\frac{V_{k+1}+V_k}{2}=\frac{X_{k+1}-X_k}{T_k}$ is the representative velocity, M,B are inertia and damping matrix, respectively, and F_k is the total force acting on the body.

Moreover, to eliminate the inherent coordination error in virtual coupling without increasing its stiffness indefinitely, we extend the framework of combining virtual coupling and *passive decomposition* [3] for our 6-DOF serial-linked type haptic device and the $SE(3)$ virtual tool. Passive decomposition uses feedback (i.e., spring-damper virtual coupling) and feedforward control to eliminate coordination error (i.e., the shape system (1)), and adjust its coordinated dynamics (i.e., the locked system (2)).

$$M_E\ddot{q}_E+C_E\dot{q}_E+C_{EL}v_L=T_E+F_E \tag{1}$$
$$M_L\dot{v}_L+C_Lv_L+C_{LE}\dot{q}_E=T_L+F_L \tag{2}$$

As a result, rendering stiffer contacts with close to zero coordination error is possible, further increasing Z-width.

For implementation, the environment and human forces are required for passive decomposition. While the environment force is available from the simulation, human force is not, due to common absents of force sensors in most commercial haptic devices. To circumvent this, we adopt a momentum-based disturbance observer [2] to estimate human forces, whereas the previous work [3] used a rather simple observer only applicable to 3-DOF devices.

3 Experimental Results

For validation, while maintaining the simulation at 1,000 [Hz] as a reference, the maximum achievable stiffness of virtual coupling $K_{vc}|_{max}$ is obtained by gradually increasing it until the device (due to its intrinsic bounded damping [3]) or the proxy (due to passivity violation) becomes unstable. Here, $SE(3)$ virtual tool is rendered as a rigid body with very light constant mass/inertia 0.01 [kg] and damping 0.1 [Ns/m]. As a result, the standard virtual coupling (i.e., explicit Euler integrator) displays $K_{vc}|_{max} \approx 100$ [N/m] whereas $K_{vc}|_{max} \approx 375$ [N/m] for the PMI — increasing Z-width by rendering larger virtual stiffness.

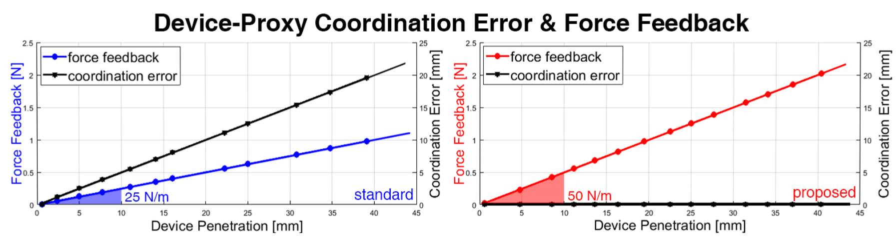

Fig. 2. Device penetration v.s. device-proxy coordination error and force feedback plot (Left: standard, right: proposed).

Moreover, with stiffness of virtual coupling/object both at 50 [N/m] and simulation at 1,000 [Hz] as a reference, device-proxy coordination error $X_{E,k}$ in the standard virtual coupling is as large as 20 [mm] (left of Fig. 2) for a unit force feedback, whereas it is maintained at $X_{E,k} \approx 0$ [mm] with passive decomposition (right of Fig. 2). This significant reduction in coordination error contributes to further increase of Z-width.

Overall, in Fig. 2 the displayed stiffnesses, under the same conditions, for the standard and proposed method are about 25 and 50 [N/m], respectively, implying our proposed simulator displays larger Z-width. However, since our simulator can render larger stiffness, at which the standard becomes unstable, it can display even larger Z-width by increasing virtual stiffnesses.

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