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Exact discrete-time stability analysis of multi-DOF haptic rendering: Impact of multi-rate, time-delay, and mechanical parameters

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Abstract

Previous studies on the stability analysis of haptic devices have predominantly focused on single-DOF devices, thereby limiting attention to multi-DOF devices, particularly those employing multi-rate sampling schemes. In this paper, we introduce a formulation for the coupled dynamics between the haptic device and the virtual environment for a multi-DOF haptic device controlled using a dual-rate sampling scheme. Subsequently, we analyze its stability through the application of a dynamic decoupling strategy within an exact discrete-time state-space framework while the device is engaged in rendering a virtual wall along one of its operational space coordinates. Furthermore, we explore how the combined influence of the dual-rate sampling approach, time delay, and the mechanical design affects the stability boundaries of the multi-DOF haptic device at a fixed workspace location as well as within the entire usable workspace. Additionally, we utilize a model-order reduction (MOR) framework to simplify the determination of the device's stability limits, irrespective of the specific combinations of time delay and sampling rates employed.

Keywords

Haptic interface, dual-rate sampling, multi-DOF, stability, *Z-width*, model-order reduction

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Introduction

Human-machine interfaces (HMIs), such as head-mounted displays, headsets, body suits, and haptic devices, form an integral part of teleoperated and extended reality systems by enabling information exchange between the rendered environment and the user.[1] Among these HMIs, haptic devices facilitate bidirectional interaction through the sense of touch, conveying information about the geometrical, inertial, and material properties of remote or virtual objects.[2] The incorporation of haptic-based feedback in virtual and remote interactions offers significant benefits, such as reducing cutting forces in remote or virtual surgery,[3] assisting sound localization in hearing-impaired individuals,[4] and enhancing the sense of immersion.[5]

Haptic devices have been designed across a spectrum, spanning from expansive full-body exoskeletons to compact fingertip-sized tactile devices.[6,7] However, the most widely adopted category in both research and commercial spheres continues to be the grounded kinesthetic devices with force feedback, known as *impedance-type* devices.[8] For a realistic portrayal of virtual or remote environments, these devices are required to possess a wider mechanical bandwidth, often referred to as the *Z-width*.[9,10] From a structural standpoint, meeting this demand necessitates that haptic devices exhibit minimal inertia and high structural stiffness.[11] Haptic devices utilizing a parallel kinematic architecture excel in meeting these prerequisites, making them prevalent in various applications. For instance, Koehler et al.[12] have very recently developed a 5-DOF parallel haptic device with compliant linkages, while Williams et al.[13] have designed a finger-mounted 4-DOF device using origami principles. Simpler multi-DOF parallel haptic devices, such as the 2-DOF 5 bar mechanism capable of providing force feedback within a planar workspace, have found applications in various fields.[14] Such devices have

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