Passivity Control with Energy Reflection and Haptic Data Reduction for Delayed Robust Bilateral Teleoperation

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***Abstract*— Bilateral teleoperation control focuses on empowering humans to safely control remote robots in unstructured environments while receiving convincing haptic force feedback. However, the key challenge lies in achieving a stable and transparent control for a system suffering with communication delay. The *IEEE P1918.1.1 Haptic Codecs for the Tactile Internet*, currently under preparation, aims to reduce data transmission while preserving perceptual fidelity for time-delayed bilateral teleoperation control. The standard incorporates the perceptual deadband approach (DB) and the time-domain passivity approach with energy reflection (TDPA-ER).**

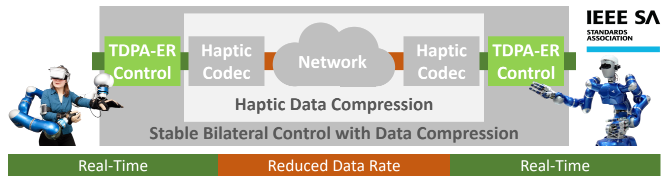

Fig. 1: TDPA-ER for low-conservatism teleoperation combined with DB, selected to become part of the haptic codec standard currently under preparation by *IEEE P1918.1.1 Haptic Codecs for the Tactile Internet*

I. Haptic Codec for Teleoperation

The advancement in teleoperation is revolutionizing industries like space exploration, medicine, manufacturing, and rescue operations. However, researchers face notable challenges, with the most significant being the inherent problem of communication delay or disruptions between the human operator side and the remote robot side. This issue introduces a tradeoff between stability, safety, and transparency, for which extensive research has been conducted over the years. To address this challenge, the development of standard has been established, known as *IEEE P1918.1.1 Haptic Codecs for the Tactile Internet* [1]. These standards incorporate a delayed robust kinesthetic codec that combines TDPA-ER [2] and DB [3], as seen in Fig. 1. These codecs solve the challenges posed by communication delays and bandwidth limitations, ensuring high potential for teleoperation.

The DB approach focuses on kinesthetic information. For position-force computed teleoperation, it transmits the velocity and force signals only when the relative difference surpasses a certain threshold. The TDPA-ER on the other hand, ensures the passivity of a two-port network, including the time-delayed communication channel that may introduce instability. The remote robot controller functions as an energy storage element. Input energy from both the human operator and remote robot is stored in the energy storage element, setting the upper bound for output energy to both the haptic device side and remote robot side. Passivity of the delayed two-port network is maintained by comparing the input and output energy at corresponding ports. Excess output energy is dissipated through adaptive damping at both the human operator and remote robot sides. Thus, TDPA-ER stabilizes time-delayed communication networks, preserves the physical coupling behavior between the haptic device and remote robot, and allows transmission of higher impedance. It is also less conservative compared to other passivity-based approaches and prevents position drift.

Therefore, the *IEEE P1918.1.1 Haptic Codecs for the Tactile Internet* will play a crucial role in advancing the teleoperation field.

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