Stability and Impedance Control Performance Limits of Latency-Prone Distributed Humanoid Controllers

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Abstract— **Humanoid robotic systems are increasingly relying on distributed feedback controllers to tackle complex sensing and decision problems, such as those found in highly articulated human-centered robots. These demands come at the cost of a growing computational burden and, as a result, larger controller latencies. To maximize robustness to mechanical disturbances by maximizing control feedback gains, this study emphasizes the necessity for compromise between high- and low-level feedback control efforts in distributed controllers. Specifically, the effect of distributed impedance controllers is studied, where damping feedback effort is executed in close proximity to the control plant and stiffness feedback effort is executed in a latency-prone centralized control process. A central observation is that the stability of high-impedance distributed controllers is very sensitive to damping feedback delay but much less to stiffness feedback delay. This study pursues a detailed analysis of this observation that leads to a physical understanding of the disparity. Then, a practical controller breakdown gain rule is derived to aim at enabling control designers to consider the benefits of implementing their control applications in a distributed fashion. These considerations are further validated through the analysis, simulation, and experimental testing on high-performance actuators and on an omnidirectional mobile base.**

I. BACKGROUND

As a result of the increasing complexity of robotic control systems, such as human-centered robots [1] (Figure 1) and industrial surgical machines, new system architectures, especially distributed control architectures, are often being sought for communicating with and controlling the numerous device subsystems. Often, these distributed control architectures manifest themselves in a hierarchical control fashion where a centralized controller can delegate tasks to subordinate local controllers (Figure 2). As it is known, communication between actuators and their low-level controllers can occur at high rates while communication between low- and high-level controllers occurs more slowly. The latter is further slowed down by the fact that centralized controllers tend to implement larger computational operations, for instance to compute system models or coordinate transformations online.

II. RESULT SUMMARY

We propose a class of distributed feedback control architectures which use stiffness servos for centralized WBOSC while realizing embedded-level damping servos as joint space damping processes [2]. Our study reveals that system stability and performance is more sensitive to damping than stiffness servo latencies. We primarily focus on analyzing,

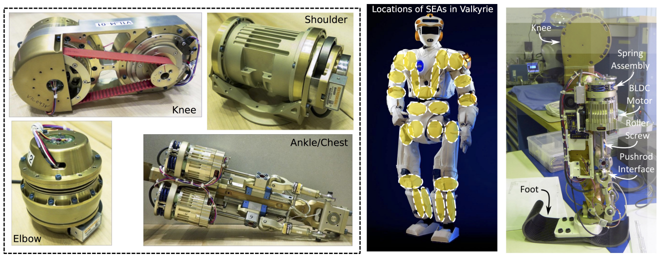

Fig. 1. Valkyrie robot equipped with series elastic actuators. The left subfigures show a set of high-performance Valkyrie series elastic actuators (SEAs) from NASA; the middle one presents the Valkyrie robot with SEA location annotations; and the right one shows the calf and ankle structure.

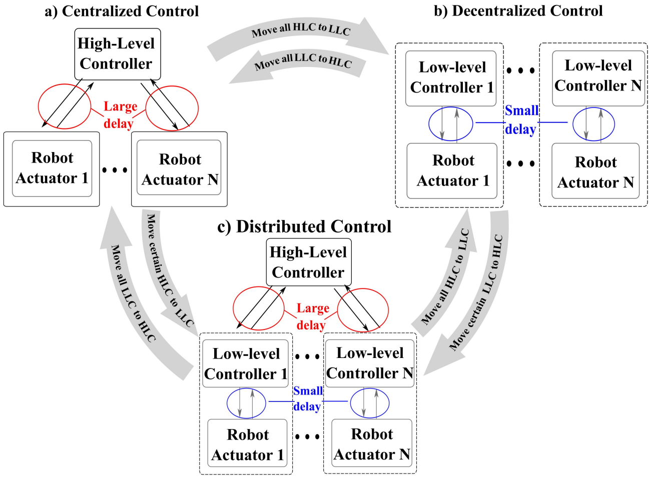

Fig. 2. Depiction of various control architectures. Many control systems today employ one of the control architectures above: a) Centralized control with only high-level feedback controllers (HLCs); b) Decentralized control with only low-level feedback controllers (LLCs); c) Distributed control with both HLCs and LLCs, which is the focus of this study.

controlling, implementing and evaluating actuators and mobile robotic systems with latency-prone distributed architectures to significantly enhance their stability and trajectory tracking capabilities. As will be empirically demonstrated, the benefit of the proposed split control approach over a monolithic controller implemented at the high level is to increase control stability due to the reduced damping feedback delay. As a direct result, closed-loop actuator impedance may be increased beyond the levels possible with a monolithic high-level impedance controller. This technique may be leveraged on many practical systems to improve disturbance

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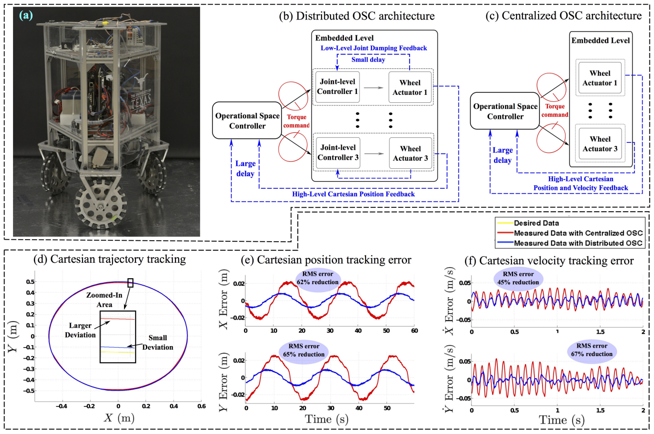

Fig. 3. Omnidirectional mobile base with distributed and centralized OSC controllers. As a proof of concept we leverage the proposed distributed architectures to our robotic mobile base demonstrating significant improvements on tracking and stability.

rejection by increasing gains without compromising overall controller stability. As such, these findings are expected to be immediately useful on many complex human-centered robotic systems.

III. EXPERIMENTAL VALIDATION

As a concept proof of the proposed distributed architecture on a multi-axis mobile platform, a Cartesian space feedback Operational Space Controller [3] is implemented on an omnidirectional mobile base. The original feedback controller was implemented as a centralized process [4] with no distributed topology at that time. The mobile base is equipped with a centralized PC computer running Linux with the RTAI real-time kernel. The PC connects with three actuator processors embedded next to the wheel drivetrains via EtherCat serial communications. The embedded processors do not talk to each other. The high level centralized PC on our robot, has a roundtrip latency to the actuators of 7ms due to process and bus communications, while the low level embedded processors have a servo rate of 0.5ms. Notice that 7ms is considered too slow for stiff feedback control. To accentuate even further the effect of feedback delay on the centralized PC, an additional 15ms delay is artificially introduced by using a data buffer. Thus, the high level controller has a total of 22 ms feedback delay.

An Operational Space Controller (OSC) is implemented in the mobile base using two different architectures. First, the controller is implemented as a centralized process, which will be called COSC, with all feedback processes taking place in the slow centralized processor and none in the embedded processors. In this case, the maximum stiffness gains should be severely limited due to the effect of the large latencies. Second a distributed controller architecture is implemented inspired by SISO controllers but adapted to a distributed Operational Space Controller, which will be called DOSC. In this version, the Cartesian stiffness feedback servo is implemented in the centralized PC in the same way than in COSC, but the Cartesian damping feedback servo is removed from the centralized process. Instead, our study implements damping feedback in joint space (i.e. proportional to the wheel velocities) on the embedded processors. A conceptual drawing of these architectures is shown in Fig. 3. The metric used for performance comparison is based on the maximum achievable Cartesian stiffness feedback gains, and the Cartesian position and velocity tracking errors.

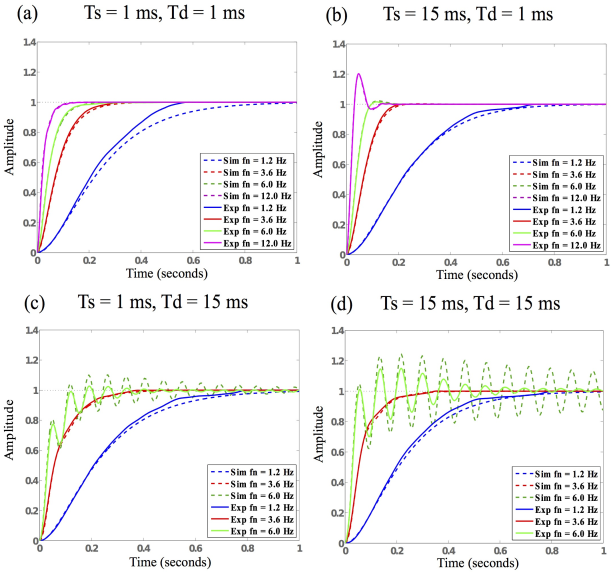

Fig. 4. Step response experiment with the distributed controller on our UT linear actuator.

IV. DISCUSSIONS

The motivation for this work has been to study the stability and performance of distributed controllers where stiffness and damping servos are implemented in distinct processors. These types of controllers will become important as computation and communications become increasingly more complex in human-centered robotic systems. Our focus on this work has been on high impedance behaviors. This focus contrasts with previous works on low impedance control. However, both high and low impedance behaviors are important in human-centered robotics. For instance, high impedance behaviors are necessary to attain good position tracking in the presence of unmodelled actuator dynamics or external disturbances.

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