Collocated Impedance Control of Proprioceptive Quasi-Direct Drive Actuators: High Fidelity Torque Estimation without A Torque Sensor

Sainan Zhang, Tairan Liu, Jen Sen Huang, and Hao Su*

Abstract—**The designing of actuator and control strategies with high stability and high accuracy without torque sensors has been one of the challenges in wearable robotics research. The conventional actuator typically needs torque sensors to command torque accurately to decrease the effect of unmodeled dynamics and common uncertainties. The series elastic actuators can estimate output torque via the deflection of an elastic element but add additional components (like springs), size, mass, and complexity. In addition, the two popularized actuator paradigms often use exteroceptive sensory feedback that is known to cause non-collocated sensing problems upon collision, which results in human-robot-interaction instability. To solve these challenges, we developed a collocated impedance control based on proprioceptive quasi-direct drive (QDD) actuators to improve stability and high accuracy for our knee exoskeleton. The proposed controller with torque estimator can compensate for the transmission losses and render more accurate impedance control but does not need a torque sensor as signal feedback. The torque sensorless significantly improves the lightweight and cost-effectiveness of wearable robots. Root locus results demonstrate our collocated system is exponential stable. Torque estimation results were evaluated in human walking tests. The RMS error of the estimated torque (without sensor) is only 0.68 Nm (5.3% of the peak of 12 Nm), while the torque tracking RMS error is 0.58 Nm (with torque sensor, 4.8%), indicating our design can render a more extensive stability region without a torque sensor for feedback while keeping equivalent accuracy to the ones with torque sensors.**

Index Terms— **Collocated Impedance Control; Quasi-Direct Drive Actuator; Wearable Robot; Torque Sensorless; Torque Estimation.**

I. Introduction

Wearable robotic systems — like exoskeletons and prostheses — have the potential to restore and enhance human mobility [1, 2]. The wearable robot is highly dynamic to meet different movement requirements of users, such as walking, running, climbing stairs, squatting, and so on. Therefore, the design of actuators and controllers to ensure safety, stability, and lightweight and manage human interactions is particularly critical for the application of wearable robots.

In the state of the art, conventional actuators [2] and series elastic actuators (SEA) [3] are widely used in the field of wearable robots, as shown in Fig. 1. In terms of the conventional actuator, due to the high gear ratio (low transparency), torque sensors are typically necessary to decrease the effect of unmodeled dynamics and common uncertainties. However, the torque sensors are often too expensive, heavy, and frangible to include in autonomous wearable robots. In terms of SEA [3], it can estimate output torque via the deflection of an elastic element. But SEA also adds additional components (like springs), size, mass, and complexity, leading many researchers to use a simple way to estimate output torque. Its output torque was estimated by the motor torque (current times torque constant), transmission (gear ratio), and efficiency. It cannot provide accurate output dynamics, and the mismatch in desired and actual output torque has yet to be quantified. In addition, since the conventional actuator and SEA both use exteroceptive sensory feedback, that is known to cause non-collocated [4-5] sensing problems upon collision, which results in human-robot-interaction instability. Therefore, to maximize the benefits of wearable robots, the need for an actuator is to become compact, torque sensorless but accurate torque estimation and stable.

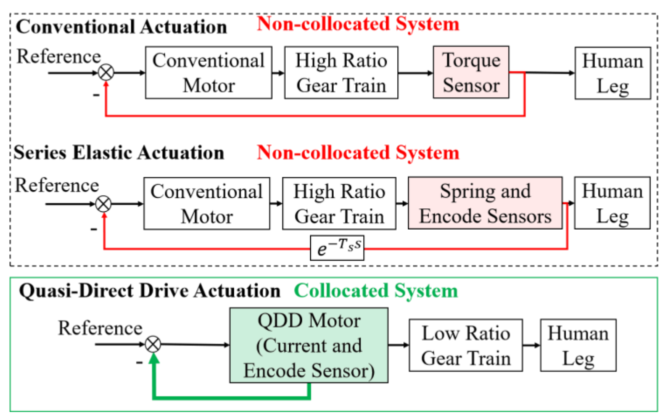

Fig. 1. Comparison of wearable robot actuation approaches: non-collocated system (conventional actuation [2] and series elastic actuation [3]) and collocated system (quasi-direct drive actuation [6]).

In summary, there are three fundamental challenges in designing actuators and controllers for wearable robots,

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including compact and lightweight hardware design, accurately command torque without a direct measurement of the output (accurate torque estimation without torque sensor), and stable control. To fill these gaps, we designed a collocated impedance control based on proprioceptive quasi-direct drive actuators. First, we customized a QDD actuator for our knee exoskeleton, which is compact and lightweight. Second, in our design, all sensors as signal feedback are placed at the force input side (motor), which is called a collocated system. It has alternating poles and zeros, making the system stable. Third, the proposed controller with torque estimator can compensate for the transmission losses and render more accurate impedance control but does not need a torque sensor as signal feedback. These advantages are theoretically motivated and experimentally validated.

II. METHOD AND RESULTS

In this work, we propose a collocated control approach based on QDD actuators. As shown in Fig. 2(A), our QDD design for wearable robots is composed of two parts: 1) the QDD actuator and 2) the wearable structure. The QDD actuator is composed of mechatronic components, including the motor and gearbox. The wearable structure is composed of purely mechanical structures that connect the wearable robot to human limbs. Our model of the control system and the plant is shown in Fig. 2(B). In our control design, we used an impedance controller for force control coupled with an internal current controller for motor control. It is worth noting that all the sensors are located on the actuator end, which is composed the collocated control scheme.

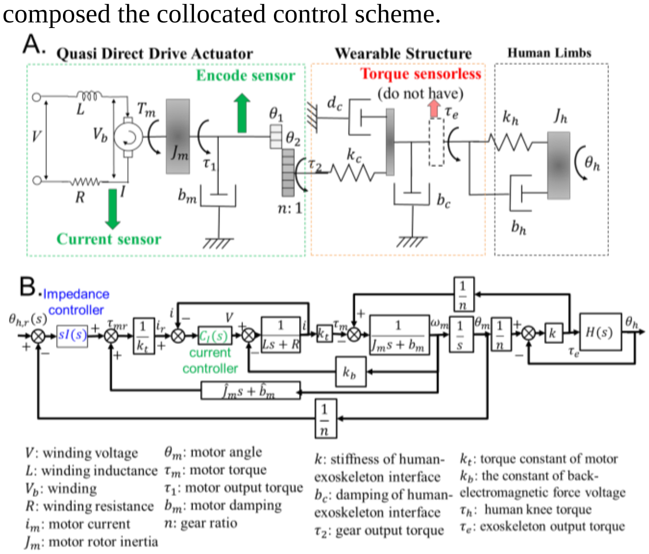

Fig. 2. Modeling of the wearable robot interacting with human limb: (A) structure of the human-robot interaction model, (B) control diagram of the wearable robot.

The collocated control system is more stable than non-collocated control in the sense that it can render a larger range of desired impedance. This is critical in the wearable robot design since this feature allows for more activities to be assisted by the wearable robots. The root locus diagrams of the collocated control scheme compared to the non-collocated control were shown in Fig. 3 (A) and (B), respectively. The root loci indicate that for the non-collocated control scheme, due to its right half plane zeros, the root locus will extend to the right half-plane when the control gains are large. However, due to the interlacing poles and zeros, the roots of the collocated control scheme will always stay in the left half-plane.

The powered walking results of our collocated control design compared to non-collocated control are shown in Fig. 3(C) and (D), respectively. The results showed that the RMSE of our design without a torque sensor is 0.63Nm (5.3% of the peak of 12 Nm, estimated torque vs. measured torque), which is just slightly larger than the result using a torque sensor (0.58Nm, 4.8% of the peak of 12 Nm) as shown in Fig. 3 (D). It demonstrated our method has a high-fidelity torque estimation without a torque sensor.

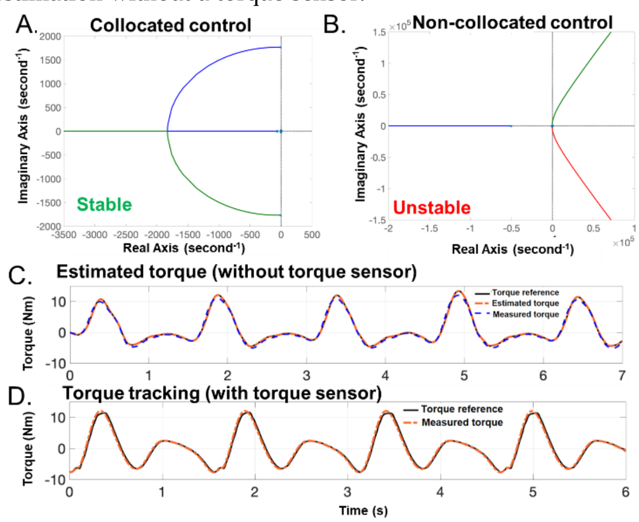

Fig. 3. The collocated impedance control design can render large range of desired impedance: (A) Root locus of our collocated control scheme. (B) Root locus of our collocated control scheme. Powered walking results of our collocated control design without a torque sensor demonstrated equivalent torque tracking error compared to the non-collocated control approach with torque sensor feedback: (C) collocated control without torque sensor, (D) non-collocated control with torque sensor.

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