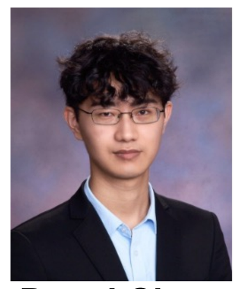
Design and Control of an Open-Source Agile Bipedal Humanoid Robot with High-Torque Density Motors for Household Assistance

NC STATE UNIVERSITY

UNC Joint Department of BIOMEDICAL ENGINEERING



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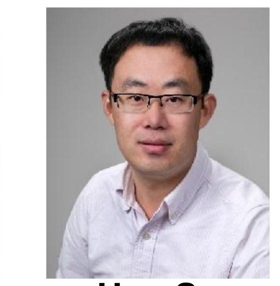

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BIOMECHATRONICS AND INTELLIGENT ROBOTICS

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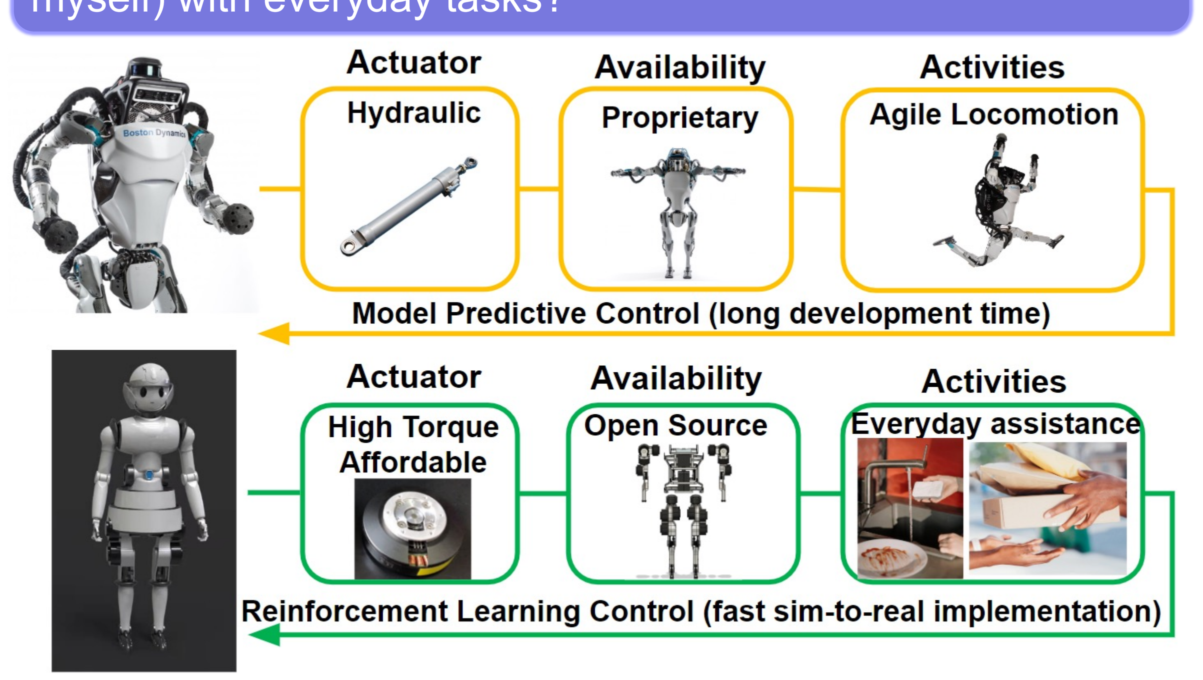
Objectives and Challenges

- There is a pressing need for elder care solutions in the US, particularly for those aged 65 and above.
- The existing elder care system mainly relies on nursing home service workers.
- Humanoid service robots have the potential to provide an alternative solution for elder care.
- The complexity of current humanoid systems limits their accessibility to most institutions.
- State of the art humanoid robots use expensive and difficult to control high gear ratio actuators or hydraulics, have limited manipulation capabilities, and require long, intensive hand tuned model predictive controllers.
- In recent years, novel actuation paradigms such as quasi direct drive have been utilized to great effect. As well as model free reinforcement learning control.
- To address this gap, an open-source bipedal humanoid robot design is proposed.

State-of-the-Art Humanoid Design Paradigms

Can we make a meaningful robot to help people (such as myself) with everyday tasks?



State of the art

(Atlas pictured)

- Hydraulic (Expensive and prone to failure)
- Proprietary components
- Designed to go beyond human capabilities
- Not open source

Proposed humanoid

(Design render)

- Quasi-direct-drive actuation
- Off-the-shelf components
- Designed to assist humans
- Open Source

Publications

[1] Zhang, Liu, Huang, Huang, Swami, Su, "Collocated Torque Control of Untethered Exoskeleton Without A Torque Sensor: Stability Enhancement and Torque Estimation", in preparation

[2] Luo, Androwis, Adamovich, Nunez, Su, Zhou. "Robust walking control of a lower limb rehabilitation exoskeleton coupled with a musculoskeletal model via deep reinforcement learning" J NeuroEngineering Rehabil 20, 34 March 2023.

[3] Yu, Huang, Lynn, Sayd, Silivanov, Park, Tian, Su. Design and Control of a High-Torque and Highly-Backdrivable Hybrid Soft Exoskeleton for Knee Injury Prevention during Squatting . *IEEE Robotics and Automation Letters* , 2019

[4] Yu, Huang, Yang, Jiao, Yang, Chen, Yi, Su. Quasi-direct drive actuation for a lightweight hip exoskeleton with high backdrivability and high bandwidth. *IEEE Transactions on Mechatronics* , 2020.

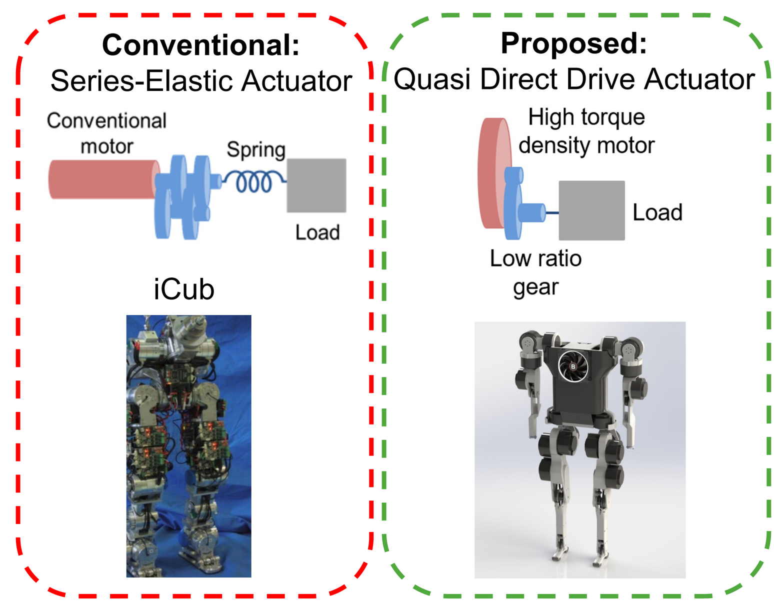
[5] Huang, Zhang, Yu, MacLean, Zhu, Di Lallo, Jiao, Bulea, Zheng, & Su, Modeling and Stiffness-based Continuous Torque Control of Lightweight Quasi-Direct-Drive Knee Exoskeletons for Versatile Walking Assistance, *IEEE Transactions on Robotics*, 2022

[6] J. Zhu, C. Jiao, I. Dominguez, S. Yu, H. Su, "Design and Backdrivability Modeling of a Portable High Torque Robotic Knee Prosthesis With Intrinsic Compliance For Agile Activities", *IEEE/ASME Transactions on Mechatronics*, 2022

Legged Robot Design Philosophy

- Backdrivable
- High bandwidth
- High torque
- No torque sensors

Quasi Direct Drive ➡ High Torque ⬆ ➡ Low Gear Ratio ⬆ ➡ Low Cost ⬇



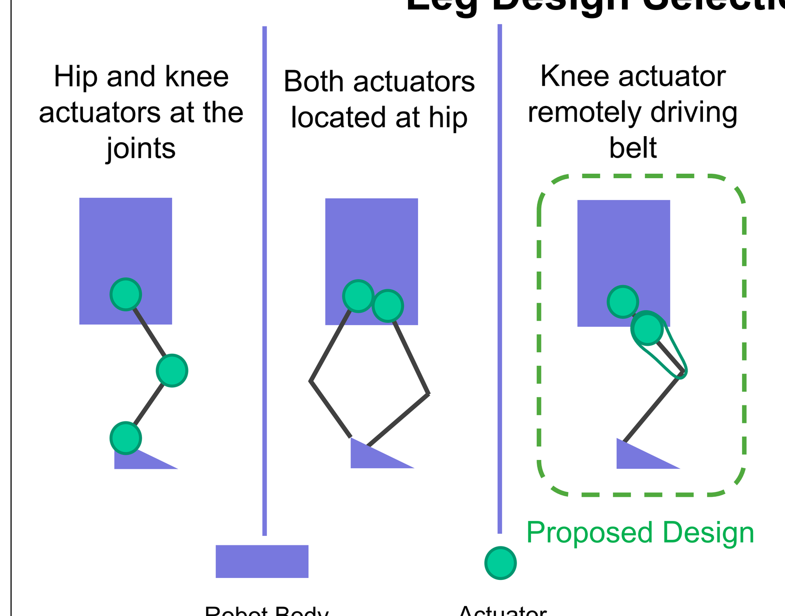
SEA

- Low bandwidth ✗
- High torque ✓
- Backdrivable ✓
- Requires torque sensor ✗

QDD

- High bandwidth ✓
- High torque ✓
- Backdrivable ✓
- Current based torque estimation ✓

Leg Design Selection



Advantages:

- Lower limb mass at distal extremities.
- Lower limb inertia
- Can use heavy and powerful actuators for all joints
- Simple mechanical belt drive transmission
- Isolation from impact shock of ground contact

Design of an Open-Source Humanoid

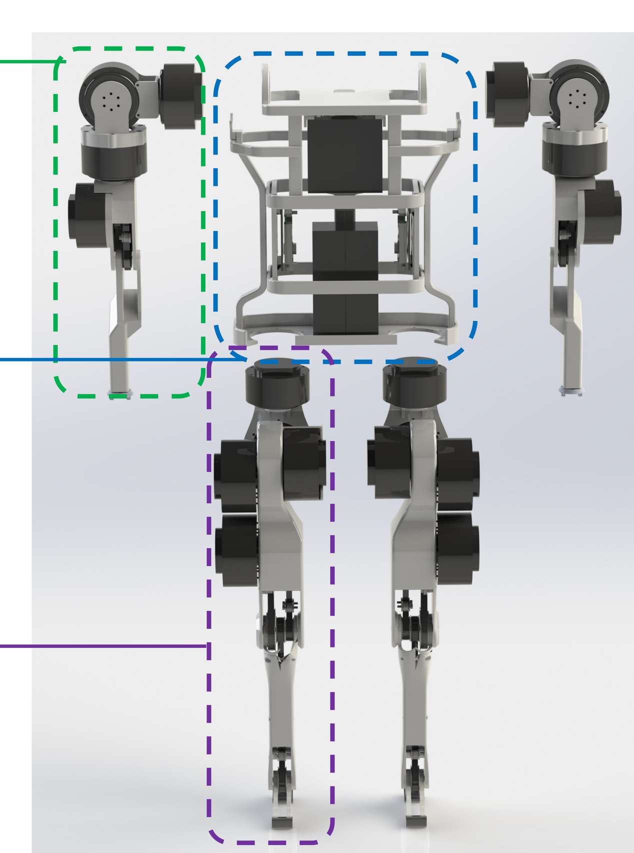
In this work, we propose the design of an open-source humanoid for household elder assistance with novel design paradigms.

- Actuators based on novel quasi-direct-drive paradigm for joint mechanisms.
- Time-efficient model-free reinforcement learning control strategies for efficient robot control.
- Combining proprioceptive feedback with exteroceptive intelligent computer vision-based navigation planning for improved mobility.

Arm Module:
- 4-dof
- Attachable hand
- 108 Nm peak torque at elbow
- Belt driven

Torso Module:
- 20k mAh battery
- Hot-swappable components
- AI capable Jetson computer
- Expandable electronics architecture

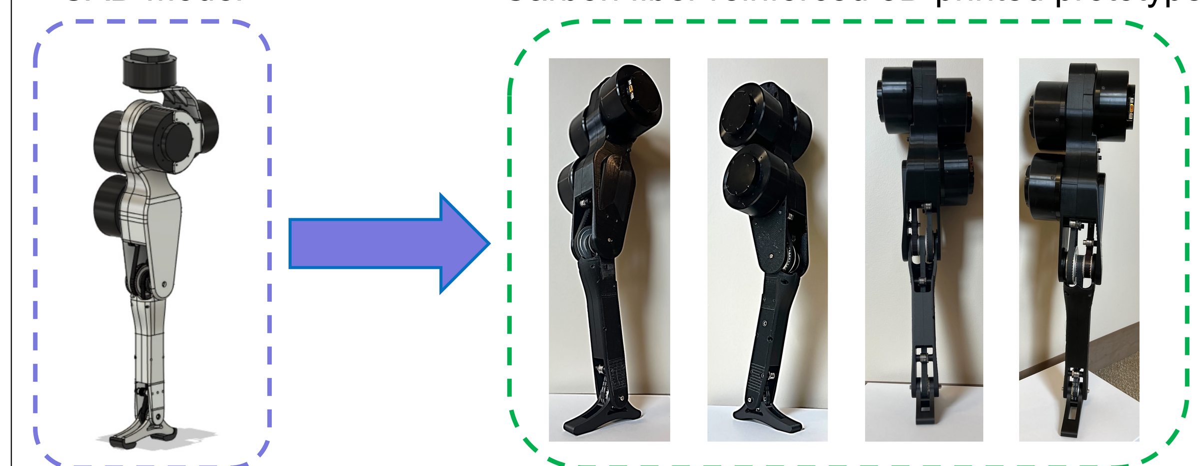
Leg Module:
- 5-dof
- 142 Nm peak torque at knee
- Belt driven



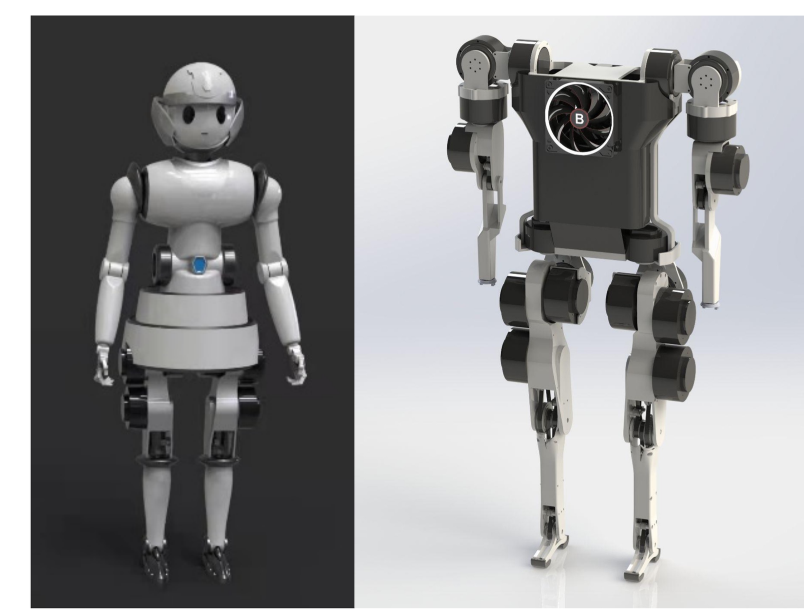
Current Prototyping Results

CAD Model

Carbon fiber reinforced 3D printed prototype



Future Work



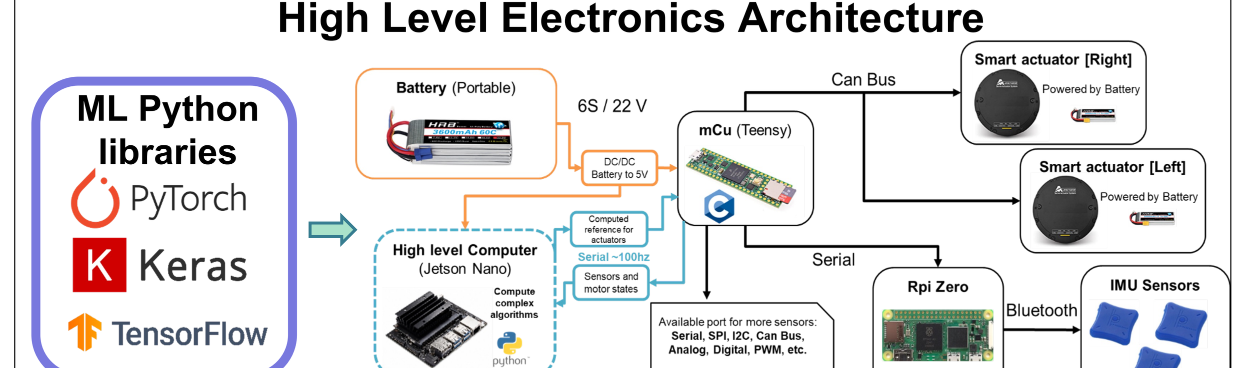
Computer renderings of the proposed bipedal humanoid robot. Initial concept rendering of a child-sized assistance robot (left). CAD design of the proposed humanoid robot (right). These visual materials aim to provide a preliminary envisioning of the final robot design.

Expandable Electronics Architecture

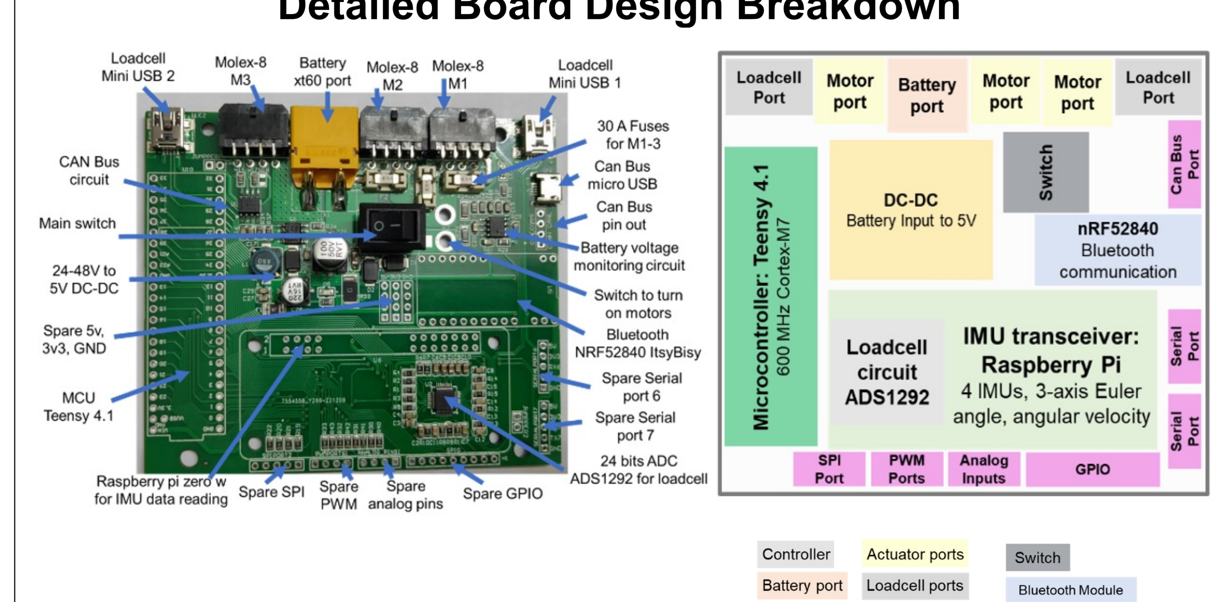
We have designed a compact, stable, user-friendly solution to drive this humanoid robot. The main features of our developed EE solutions are:

- Driving multiple actuators simultaneously, expandable up to 18 actuators.
- Multiple communication protocols for sensors, actuators, and high-level computers.
- Bluetooth communication for user interface.

High Level Electronics Architecture

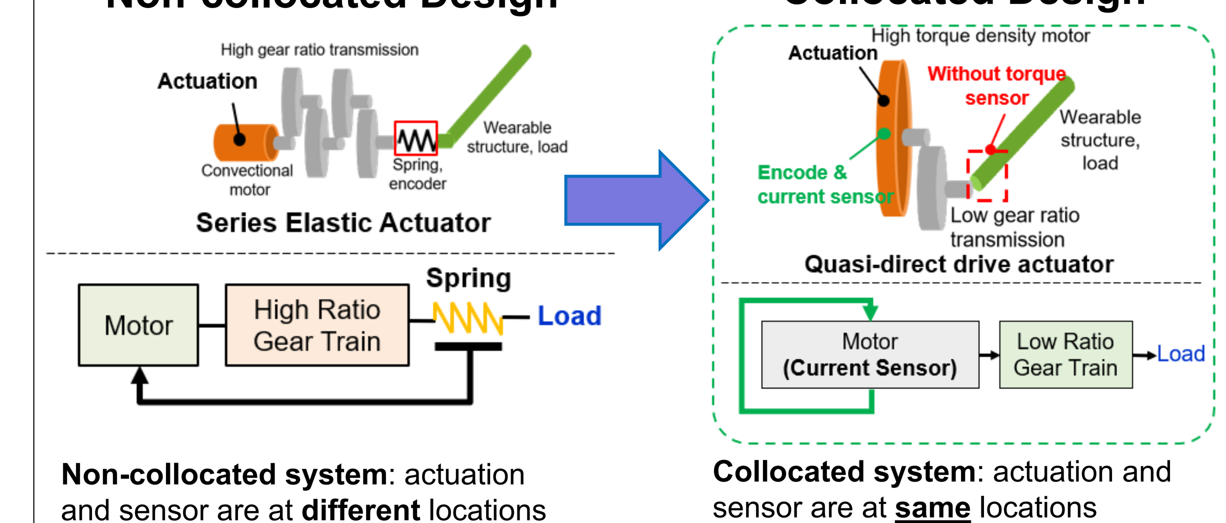


Detailed Board Design Breakdown



Collocated Control for Current Feedback Control

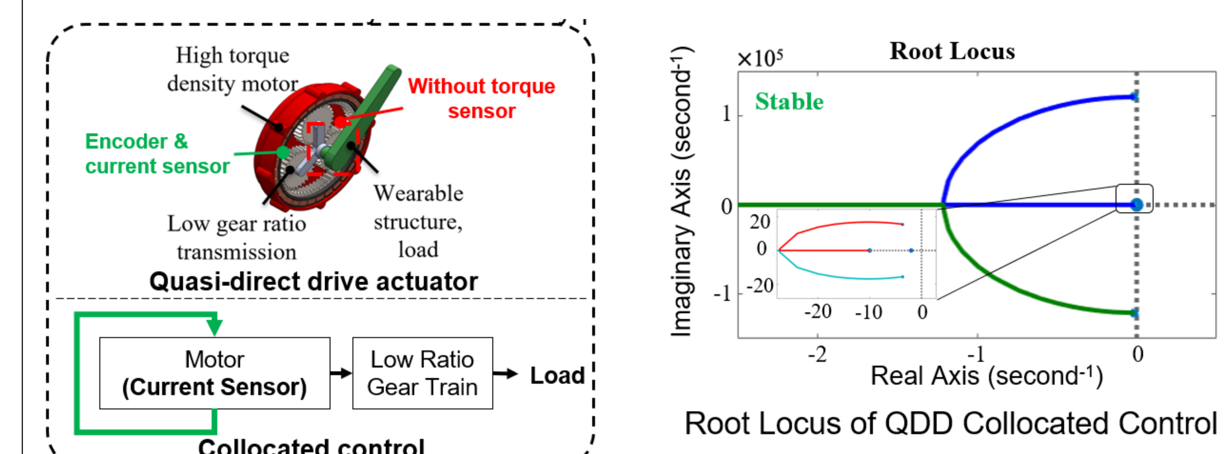
To ensure stability of low level control and take advantage of the capabilities of the quasi direct drive actuators, we developed a collocated control strategy.



Non-collocated system: actuation and sensor are at __different__ locations

Collocated system: actuation and sensor are at __same__ locations

- Collocated control system: exponential stability
- More robust: stability not limited by parameters



Root Locus of QDD Collocated Control

- Advantages of our method
  - No torque sensor: cost-effective and lightweight
  - Simpler mechanical design, more compact
  - High-fidelity torque estimation for versatile activities

Torque estimation method:

$$\hat{\tau}(s) = n(\tau_m - \hat{J}_m\ddot{\theta}_m - \hat{b}_m\dot{\theta}_m) = \frac{\hat{k}}{\hat{k} - k_d}(k_d + b_d s) * \left[\theta_{h,r}(s) - \frac{1}{n}\theta_m(s)\right]$$

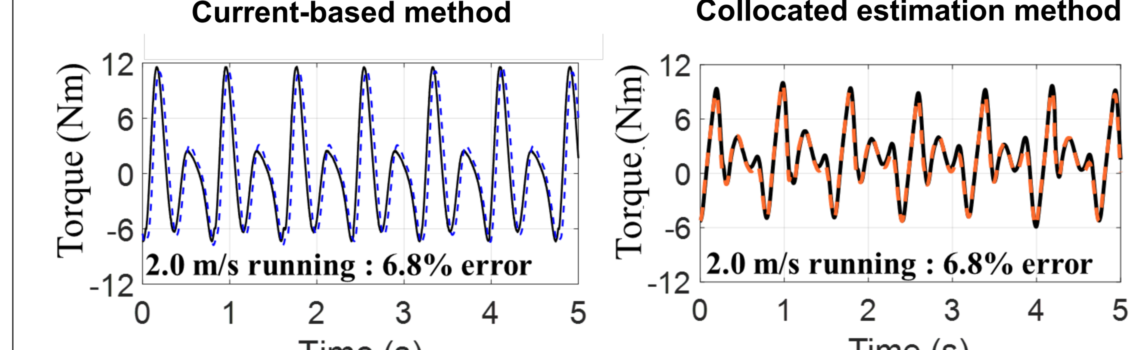
- $\frac{\hat{k}}{\hat{k}-k_d}$: Transmission stiffness / (Transmission stiffness – Desired stiffness)
- $(k_d + b_d s)$: Desired impedance
- $\theta_{h,r}(s)$: joint angles ref
- $\theta_m(s)$: Robot joint angles

Estimate torque for activities with different frequency

Enhanced Stability + Accurate Torque Estimation

- SEA: 25% error [1]
- QDD current based estimation: 10% error
- QDD our torque estimation : 3-5% error

	1 m/s	1.5 m/s	2.0 m/s
Current based torque estimation (QDD)	12.4%	15.8%	16.3%
Our torque estimation method (QDD)	3.7%	3.6%	5.0%



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