Low-Cost Biomimetic Yank-Aware Proprioceptive Actuator **Jared Grinberg**

The advent of proprioceptive actuators, pioneered in the MIT Cheetah robot,[1,2] has led to a flourishing of legged robot designs. However, while much progress has been made in legged and bipedal locomotion, achieving truly smooth animal-like robotic motion remains an active challenge in the field.[3]

There have been a number of attempts to design control mechanisms that try to overcome this issue, such as the use of Proportional-Integral-Derivative (PID) smoothing,[4,5] reinforcement learning (RL),[6] and human-in-the-loop training protocols.[7] All of these approaches have significant downsides. PID smoothing must be tuned to the specific motion[4] and is therefore not generalizable to autonomous locomotion. While RL-based approaches have been very impressive in achieving general success in executing physical tasks, they have resulted in jerky motion once implemented on physical robots, posing serious safety and wear-and-tear concerns.[6] So far, only human-in-the-loop training protocols have approached the fluid motion present in animal models, but human feedback for such protocols is expensive, making them hard to scale.[7]

My **hypothesis** is that much of the challenge in achieving smooth robotic motion lies in insufficiently rich sensory input into the control algorithm. I further hypothesize that, taking inspiration from the sensory modalities known to be used by animals in controlling their movement, we can endow an actuator and its control algorithm with the capacity to perceive and use those sensory modalities.

One obvious avenue for enriching the sensory inputs into the control algorithm is to use the desired output force vector in the loop of the control algorithm. This would extend the current paradigms of torque-based[8] and active impedance[9] control and provide a lower-cost alternative to designs that incorporate third-party force-torque sensors into the actuator assembly.[10] While multiple derivatives of position have been incorporated into modern control algorithms,[11] force is not currently a "first-class citizen" in the loop of these control systems. I propose a control algorithm using force and its derivatives because it is known that an animal control algorithm for muscle actuation does in fact rely on this information.[12] The proper technical term for one such force derivative is "yank," which is the first derivative of force over time. This term has only recently been explicitly introduced in the literature.[12]

I propose to achieve the above control algorithm by integrating force-sensing strain gauge arrays into the actuator design (Fig. 1) and then incorporating data about force and ***yank*** into the loop of a field-oriented control (FOC)-style algorithm. The end goal of my project would be to release an open-source design of a novel lightweight, inexpensive, high-dynamic-range actuator with an integrated controller and force sensing capability, and to assemble a reference legged robot which I will then use to demonstrate the movement capabilities that can be achieved.

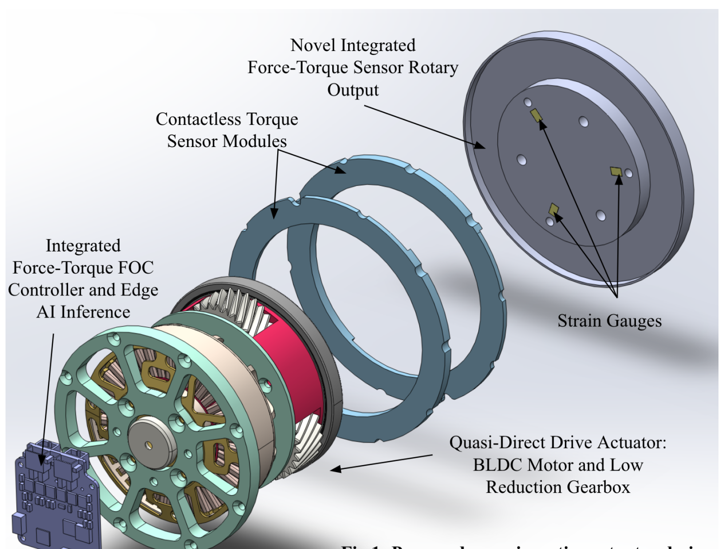

Fig 1: Proposed proprioceptive actuator design.

Project Objectives

Objective 1: Design a mechanical actuator with integrated force sensing capability. I will create a mechanical design of the actuator with integrated strain gauges. The actuator will contain a custom-designed integrated force-torque sensor, a quasi-direct drive (brushless DC motor with low reduction ratio), and an integrated controller board. After the mechanical design is complete, I will develop a calibration procedure for the strain gauges to ensure I can obtain a linear force signal from them. Validation will be done by comparing the force readings against a reference 6-axis force sensor under standardized loads.

Objective 2: Incorporate the force data into the control loop. This will require integrating force readings into the feedback loop of the control algorithm. The first stage will involve training an AI algorithm to be used by the controller board to predict optimal PID values. The feature vector for this task will comprise ***yank***, other multiple derivatives of force and position with respect to time, as well as other electromagnetic data from the motor controller. This will result in the establishment of a baseline algorithm. The second stage involves completely replacing the FOC/PID algorithms with an end-to-end AI model. Lastly, validation will involve performing a complete characterization of the actuator using the novel control algorithm and comparing it to the characterization using a standard FOC controller.

Objective 3: Create a reference design of a legged robot to evaluate complex motion that can be obtained by using the novel actuator and control algorithm. This will start with the design and assembly of a legged robot using the new actuator and creating a Robot Operating System (ROS) simulation model of the robot. Validation will involve characterizing the motion of the legged robot for complex motions like jumping, running, and balancing on unsteady surfaces. This will require training two RL-based models to control the robot for these actions - one using the force-aware controller and another using standard FOC control. The two models will then be qualitatively and quantitatively compared against each other using the standardized set of benchmarking motions.

Intellectual Merit

There currently exist no actuators or motors that can directly incorporate force and its time derivatives into the control loop. While prior work has created ultra-thin torque sensors for robotic actuators,[13] no sensor has been embedded into the actuator body itself. Also, while AI is actively used for motor speed control,[14] there currently exist no AI-driven force-based actuator controllers. Development of such a proprioceptive actuator will allow us to determine whether it is possible to achieve more animal-like natural motion and will act as a stepping stone to developing new types of robotic control. This work also adds to the understanding of human and animal motion control via the construction of higher-fidelity physical models and control algorithms. Such an actuator would allow for more effective use of force and its derivatives as real-time input parameters into AI-driven robotic control algorithms.

Broader Impacts

The introduction of inexpensive brushless direct current motors with FOC control has enabled new research directions and innovation in the field of autonomous robotic locomotion. My proposed research will contribute to this advancement and serve as an excellent foundation for my future research career in this area, as well as having broader societal benefits. For example, enabling fluid, animal-like motion in robots would significantly expand their use in collaborative and supportive applications that require the robot to have movement characteristics similar to that of a human. Such applications include exoskeletons, in-home robotic assistants for disabled and elderly individuals, movement rehabilitation devices for neurological disorders, etc. I am also passionate about using this research project to mentor students from underrepresented communities, both by engaging them in parts of the project directly and by using the resulting legged robot as a platform for educational activities in robotics and STEM (for example, to demonstrate physics concepts in the context of locomotion or to teach introductory robotic control and embodied AI courses). I believe that a low-cost proprioceptive actuator with force-aware FOC control will have a large impact on accelerating robotics education in general, similar to how the advent of MIT Cheetah and quasi-direct drives has had a profound impact on the hobbyist roboticist community.

References: [1] Wensing P.M. et al. IEEE Transactions on Robotics. 2017;33(3):509. [2] Katz B.G. Diss. Massachusetts Institute of Technology. 2018. [3] Zhao Y. et al. IEEE Access. 2023;11. [4] Hernández-Guzmán V.M., Orrante-Sakanassi J. International Journal of Control. 2021;94(2):267. [5] Merugumalla M.K., Navuri P.K. i-Manager's Journal on Instrumentation & Control Engineering. 2016;5(1). [6] Ibarz J. et al. The International Journal of Robotics Research. 2021;40(4-5):698. [7] Lee K., Smith L., Abbeel P. In pre-print. (2021). [8] Liu Y., Zhu Z.Q., Howe D. IEEE Transactions on Industry Applications. 2006;42(5):1275. [9] Lund S.H.J., Billeschou P., Larsen L.B. Actuators. 2019;8(4):71. [10] Kim Y.B. et al. IEEE/ASME Transactions on Mechatronics. 2018;23(4):1662. [11] Mohanraj D. et al. IEEE Access. 2022;10. [12] Lin D.C. et al. Journal of Experimental Biology. 2019;222(18). [13] Seok D.-Y. et al. IEEE Robotics and Automation Letters. 2020;5(4):5873. [14] Beladjine D.E. et al. 2021 18th International Multi-Conference on Systems, Signals & Devices (SSD). 2021;1291.