Recent technological advances in computer vision and embedded systems will allow mobile robots to become essential tools in our society. Legged robots provide versatile mobility for rough terrain exploration and adaptability to human environments. However, current state-of-the-art legged robots are not yet comparable to humans and animals in terms of agility and robustness to navigate in real-world environments. As a robotics engineer, I aspire to device robust and versatile legged robots capable of all-terrain mobility for service and emergency applications. In my previous research, I focused on optimizing control algorithms to accomplish advanced dynamic locomotion. In the dynamic motion control, the role of control algorithms is crucial, but I also found the importance of understanding how the combination of hardware and control affects the limits of achievable behavior. To this end, my major aims are to: 1) **design a new control architecture that combines the benefits of model-based controllers and machine learning techniques to accomplish agile and autonomous mobility** and 2) **create a unified framework to co-develop controller and hardware for maximizing the capability of legged robots**.

Previous Research

Dynamic locomotion of passive-ankle biped robots

During my PhD at the University of Texas at Austin, my main project was to design a real-time control architecture for dynamic locomotion of a passive-ankle bipedal robot. The project was motivated by the fact that most biped robots walk statically or quasi-statically because they heavily rely on ankle actuation and the use of a footprint for support. The major contributions of this project on legged locomotion research are two folds:

First, I devised a control architecture that enabled dynamic biped locomotion by incorporating two techniques called joint-level feedback control and whole-body control (WBC). Earlier versions of WBC have been used for humanoid robot control but have never been tested before in point-foot dynamic locomotion. The main reason for this limitation stems from the use of cascaded feedback structures in WBC which are sensitive to time delays, disturbances, and noise. My methodology circumvents these issues by properly distributing the balance feedback duty to WBC and joint position feedback controllers based on each feedback controller's performance characteristics such as bandwidth and stability.

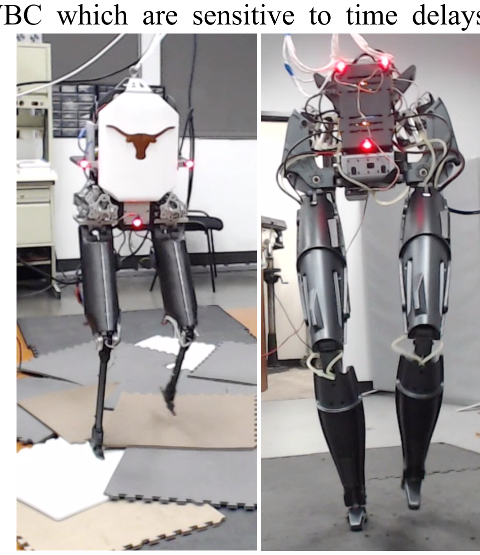

Fig 1. Dynamic locomotion of biped robots

Second, I designed a type of locomotion planners for biped balance and walking endowed with an uncertainty analysis to find acceptable control and sensing errors. I utilized robust control theory on my step location planner to compute acceptable landing location and center of mass state estimation errors. I optimized the biped robot hardware, computational controllers, and state estimators to satisfy the error limits. These elaborate improvements led to the successful demonstration of dynamic locomotion of two advanced bipedal robots capable of dynamic walking.

In this project, I published seven conference papers [1, 2, 3, 4, 5, 6, 7], one journal paper [8], and another journal paper is currently under review [9]. The publication in IEEE Transactions on Robotics [8] was nominated as a finalist for best whole-body control paper and a finalist for best whole-body control video. The paper published in IEEE International Conference on Humanoid Robots [2] was selected as an outstanding paper. This work has also been highlighted in several media channels including IEEE spectrum, Discovery Channel Canada, Seeker (370k views), KVUE news, UT Austin News, and The Daily Texan, etc.

Highly dynamic and versatile quadruped locomotion

At MIT, I have built upon the work at UT Austin by combining WBC and Model Predictive Control (MPC) to overcome the fundamental limitations of WBC. WBC accounts for only instantaneous states and cannot manage well the non-contact phase, such as jumping or running. I formulated a new method, Whole-Body Impulse Controller (WBIC), which follows reaction force profiles computed via MPC rather than following the desired body trajectory. By employing a hybrid control approach with MPC and WBIC, the Mini-Cheetah robot, a small quadruped the size of Terrier dog, demonstrated untethered running at 3.7 m/s, becoming the third-fastest speed accomplished by a legged robot and the fastest among the similar size quadruped robots (Fig 2a). During experiments, Mini-Cheetah operates at the boundary of the actuator's torque and power limits, demonstrating that my controller is able to achieve the maximum dynamic capability of the robot.

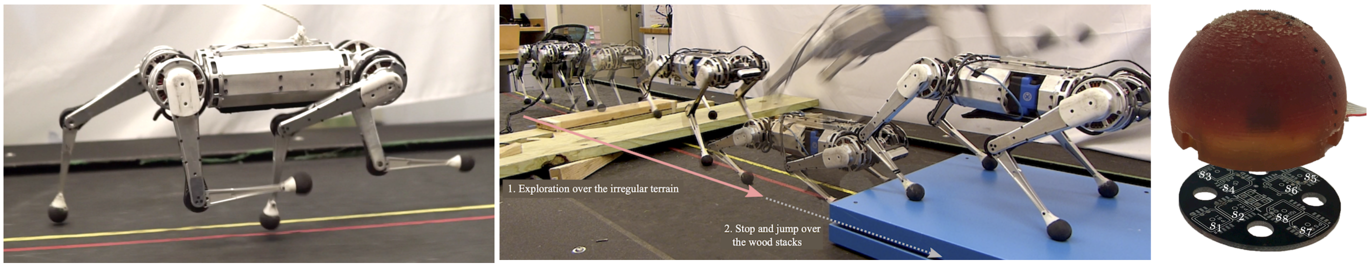

Fig 2. (a) Mini-Cheetah robot running at 3.7m/s using whole-body impulse controller, (b) Mini-Cheetah can explore unstructured terrain and jump over obstacles, (c) Impact-resilient foot sensor for force and contact angle measurement

To advance research on real-world rough terrain locomotion capabilities of small quadruped robots, I integrated vision sensing and developed a dynamic jumping behavior using the control architecture of my design. I implemented a computationally efficient perception software and walking algorithms to run on a small computer, while still making the entire system effective for rapid walking over obstacles higher than 1/3 of the robot's leg length. The walking and jumping experiment over unstructured terrains shown in Fig. 2(b) is one of the most dynamic rough-terrain locomotion accomplished by a legged robot.

In legged locomotion, detecting contact and measuring contact forces is fundamental, but most contact sensors are vulnerable to impact caused by fast stepping behaviors. To address this issue, we developed an impact-resilient foot sensor consisting of eight pressure sensors covered by a hemispherical polyurethane rubber. The challenge was to find the mapping from pressure signals to contact forces and angles. I employed a supervised learning technique, Gaussian Process Regression, and obtain accurate force and angle estimation while effectively addressing the complex relationship between contact forces and stress distribution in the urethane rubber [10]. The measured forces will help the balance control and smooth transition between the stance and swing tasks, which will enhance the stability and overall performance of legged robots.

Future Research Agenda

In the future, I will advance the capability of legged robots by 1) developing computational methods to optimize hardware design for dynamic motion, 2) enhancing the autonomy of legged robots, and 3) optimizing controller and hardware for dynamic motion assist using exoskeleton robots. Herein I present the long-term visions for three projects and highlight the achievable short-term objectives for each.

Unified framework to co-develop controller and hardware for dynamic capability

The current robot hardware design process heavily relies on the designer's experience and intuition rather than quantified analysis. Because of the lack of analytical method to evaluate which design is better than the other, people can easily fall into a wrong common sense. For instance, prior to the MIT cheetah robot, the legged robot community generally believed that quadruped robots must use hydraulic actuators to perform dynamic locomotion. However, dynamic locomotion demonstrated by the electrically actuated MIT cheetah robot showed that electric actuators can outperform hydraulic actuators. The reason for the difficulty in the design evaluation is that the dynamic capability of a robot depends also on controllers as well as the hardware. To address this issue, I will create a unified framework to co-develop the controller and hardware for maximizing the performance of legged robots.

As the first step toward my long-term goal, I will develop a computational method to simultaneously optimize actuators, a topology of a robot, and its controller. In the legged robot design, deciding proper actuator torque is challenging because the entire actuator mass, which increases as output torque becomes higher, should be lifted by a leg. In particular, designers have to simultaneously consider mass-torque relationships and the robot topology, which define workspace, kinematic singularity, mass distribution, etc. Those design parameters are tightly related to the targeted dynamic capability of the robot and its controller, but the algorithm to quantify the relationship does not exist. I plan to utilize my locomotion controller that can demonstrate the maximum agility of given hardware to find the relationship between a robot's dynamic capability and its hardware design. Based on my previous studies on actuator [11] and locomotion control, I will develop a method to find the best robot design by exploring the complex correlation between controller and design parameters. For the funding of this research, I plan to apply for NSF - Cyber-Physical Systems (CPS), NSF - Dynamics, Control and Systems Diagnostics (DCSD).

Enhancement of athletic intelligence

In my future research, I will pursue enhancing the 'athletic intelligence' of legged systems to make legged robots more agile and reliable, which will eventually make them practical and useful. Athletic intelligence of legged robots refers to the complex motion coordination that incorporates the rapid perception of the external environment to guarantee the execution of a locomotion task such as moving quickly from one place to another. Approaching this complex problem using analytical methods is not practical, but solely relying on data-driven methods also has an issue that we lose understanding of important aspects such as safety, controllability, or stability. I believe that this issue can be solved by finding a high-level motion coordinator with machine learning techniques while guiding the training process with analytical methods to be safe and understandable.

As a first step, I will integrate my locomotion controller and a high-level planner trained by reinforcement learning. The high-level planner will coordinate various locomotion and ballistic behaviors. For instance, when the upcoming obstacle is too high, the planner will autonomously initiate a jump in the middle of the run. I am currently cooperating with Google brain to combine their machine learning techniques and my controllers and will continue this cooperation in the future. NRI, ONR-Broad Agency Announcement (BAA), and NSF - Computational and Data-Enabled Science and Engineering (CDS&E) can be funding resources for this AI research.

Exoskeleton for dynamic motion support

Sharing a topology with humans is an important aspect of biped robots since the developed technology in the robot can be deployed to exoskeleton control. I have participated in the development of an exoskeleton robot for soldiers and found two problems of exoskeleton research. The first problem is a missing reliable locomotion controller for human-level biped walking of an exoskeleton robot even without a human subject. The second one is the lack of a proper sensing system embedded in the robotic suit to rapidly detect human intention. These problems can be addressed by a unified framework mentioned above. An additional complexity is the need to include sensor deployment and estimation algorithms for human intention recognition in the framework. I will develop a unified framework including a controller and sensing system to enable the dynamic motion assistant using an exoskeleton robot. In the near future, I am going to set up the cooperation with Apptronik, the company that developed the exoskeleton robot shown in Fig. 3, to assist in controller and sensing system development for the next generation of exoskeletons. For the funding of this exoskeleton research, I will apply for Mind, Machine, and Motor Nexus (M3X) and United States Special Operation Command (SOCOM).

Fig 3. Lower body exoskeleton

Also, I will apply for research funding open to young faculties such as DARPA young faculty award, ONR young investigator program, NSF career.

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