Facilities, Equipment, and Other Resources

Johns Hopkins University – Chen Li

The Johns Hopkins research community is extremely diverse and rich. There are investigators with expertise in essentially all areas that are available for consultation. The physical and intellectual environment, institutional support, and critical mass within the laboratories involved are ideal. They have helped to contribute to our productivity in the past and improve the prospect of success for the project.

Li Lab

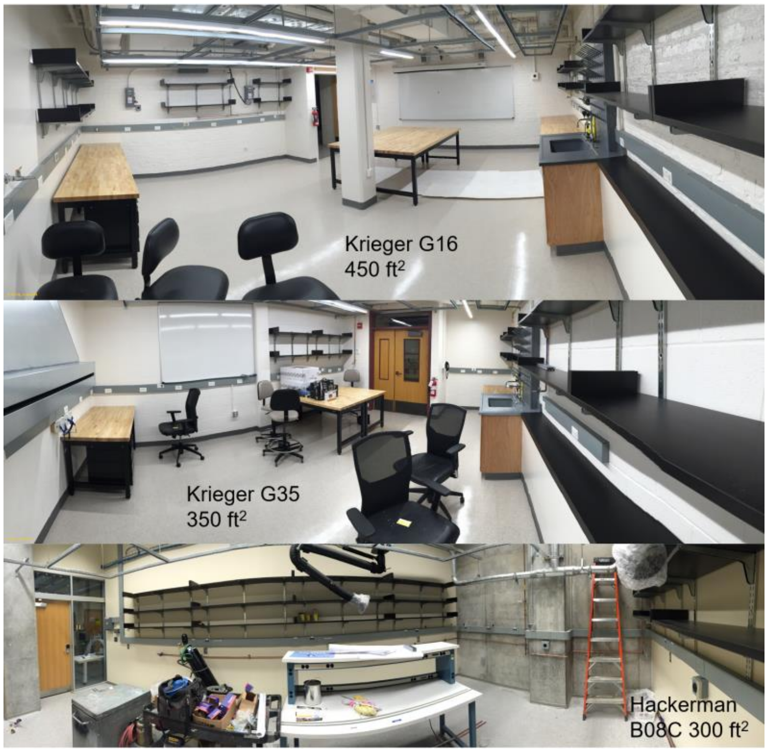

Fig. 1. Lab space.

1. Office and Lab Space

1.1. Office

Li has a furnished office (200 sq. ft.) in the Hackerman Hall. A separate office space in the same building (ca. 700 sq. ft.) houses the students of the Li group. These offices are in close proximity to the Li group lab spaces.

1.2. Laboratory

The space in the Li group (**Fig. 1**) amounts to a total of 1100 sq. ft split among Krieger Hall and Hackerman Hall on the Homewood campus of Johns Hopkins University, in Baltimore, MD. The space in Krieger Hall is divided into two rooms (Krieger G16 and Krieger G35). Each room is equipped with work benches and workstations. Krieger G16 has a vent system designed to filter small particles in the air to study locomotion on granular substrates (e.g., mud). Each room has ample space for experimental setups for animal and robot experiments besides building lab apparatus and performing data analyses and computation. Each room also has temperature control (up to 40 degrees C) for animal experiments.

2. Animal Care Facilities

Li's lab also has a 300 sq. ft. space for housing research animals (**Fig. 2**), with common areas shared with Prof. Noah Cowan's lab. The invertebrate and reptile spaces have environmental temperature and humidity control with automatic air conditioners, heaters, and humidifiers.

2.1. Invertebrate Facilities

We have an animal room for housing our invertebrates. These include various species of cockroaches, spiders, and flies. We currently have American cockroaches and discoid cockroaches housed in plastic containers. We have whip spiders and various species of jumping spiders. We also have golden hydei flightless fruit flies to feed the spiders.

2.2. Reptile Facilities

We have allocated part of our animal room for reptiles and currently have corn snakes. The housing consists of cages filled with aspen bedding and additional forms of enrichment for the snakes. The temperature is controlled using cage warmers. We have a refrigerator to store food for the snakes

2.3. Fish Facilities

We have an animal room for housing amphibious fishes in 20 and 40-gallon tanks. To investigate the appendicular, axial-appendicular, and axial locomotion, we are using three model organisms, mudskipper, bichir, and ropefish respectively. The housing consists of an R/O water outlet, a floor drain, and a sink. Each tank is temperature-controlled and has a filtration system and additional forms for enrichment for the fishes.

Fig. 2. Animal care facilities.

3. Experimental Equipment

3.1. Motion Tracking System

An 8-camera PhaseSpace motion tracking system is available in Krieger G16 with distinct active (LED) markers for locomotion experiments (**Fig. 3**):

- Capture space from 8 ft × 8 ft (up to 50 ft × 50 ft)
- High-speed motion tracking camera: 960 fps, 36000 x 360000 pixels, 60° field of view, 1-20 m range
- Upgradable to 80 cameras (with purchase)
- 144 distinct LED markers with micro wireless drivers
- Transmission latency from camera to server: 2 frames, overall latency: < 3 ms
- Tracking software supports closed-loop control of robots (with custom development)

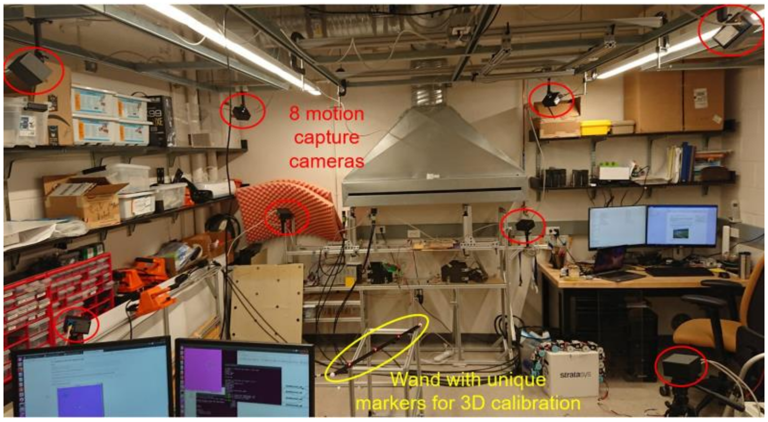

Fig. 3. Motion tracking system.

3.2. Multi-Camera High-Speed Imaging Systems

Three custom visible-light high-speed imaging systems (supporting up to 12 cameras simultaneous capture) are available in Krieger G16 and G35 for animal and robot 3-D kinematics capture (**Fig. 4**). The following cameras are available for use on these systems:

- 3 Photron Fastcam Mini UX-100, 1024 × 1024 pixels @ 4000 fps
- 4 Fastec IL5, 1920 × 1080 pixels @ 634 fps
- 4 JAI Go-5000M, 2560 × 2048 pixels @ 107 fps, color
- 24 Adimec-N5A100, 2592 × 2048 pixels @ 105 fps
- 1 PointGrey Flea3, 1280 × 1024 pixel @ 150 fps

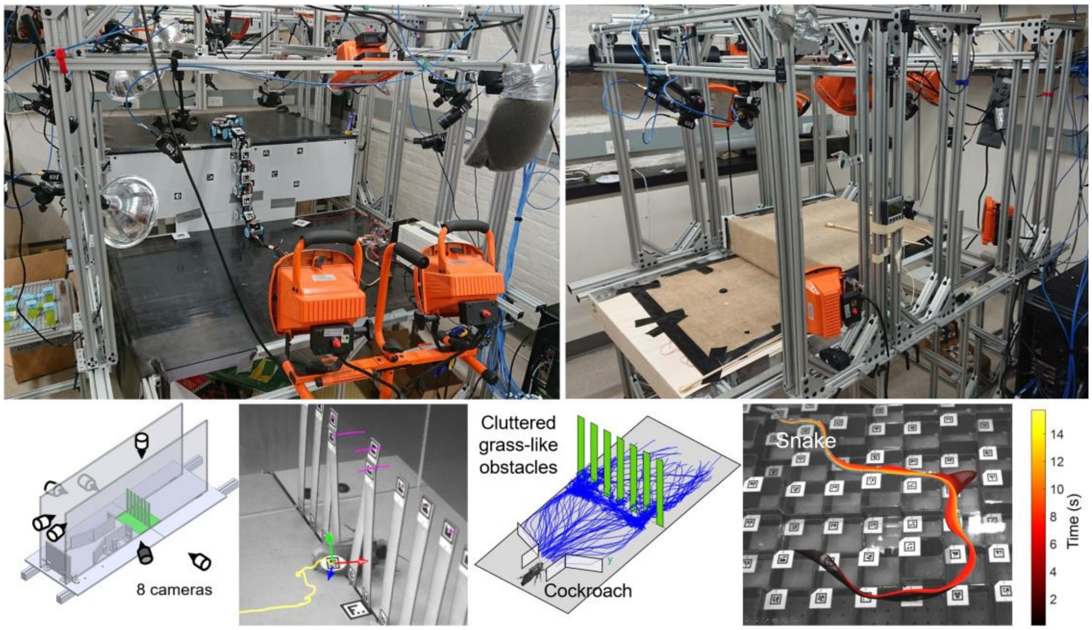

Fig. 4. Multi-camera high-speed imaging systems and examples of animal tracking.

Additional imaging equipment includes:

- 1 Nikon D3200 DSLR camera
- multiple lenses of focal lengths 12.5mm, 16mm, 25 mm, and 50 mm;
- multiple tripods
- multiple lighting stands
- multiple USB webcams
- multiple LED lights
- multiple lighting lamps

3.3. Thermal former

The lab has a large Formech 508FS vacuum former with 482 mm × 432 mm forming area (**Fig. 5**, left). It can be used to create custom complex shapes using plastic sheets of various frictional properties. This can be used for creating complex terrain (**Fig. 5**, right) as well as complex robot parts (e.g., **Fig. 10**, robot wings) for studying locomotion.

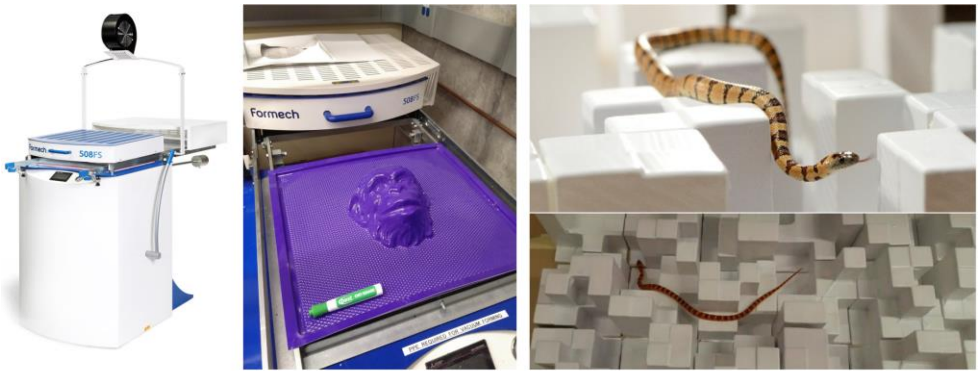

Fig. 5. Thermal former for making custom complex shapes, such as uneven terrain for studying snake locomotion in complex 3-D terrains.

3.4. 3-D printers

To construct terrain testbeds and robotic systems for experiments, the lab has three 3-D printers:

- an Ultimaker 2 Extended+ 3D printer (223 x 223 x 305 mm print area),
- an UP BOX+ 3D printer (255 × 205 × 205 mm print area),
- and an UP Plus 2 3D printer (140 x 140 x 135 mm print area).

All three printers come with various nozzle sizes and allow for nozzle temperature control to accommodate most available filament types.

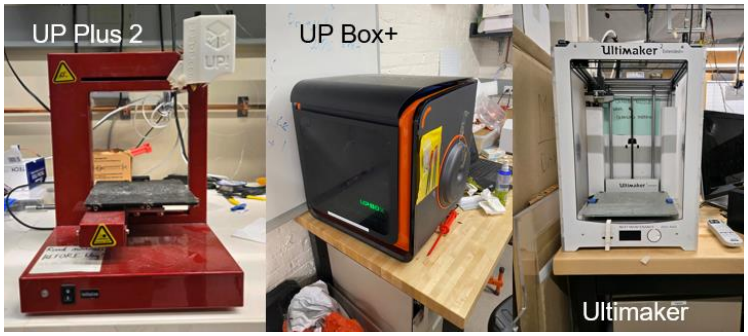

Fig. 6. Three 3-D printers.

3.5. Custom mud experiment apparatus

For locomotion studies involving wet, flowable substrates (such as mud), there is an automatic mixer (**Fig. 7,** top left) for preparing uniform substrates with controlled solid particle-to-water ratios (called the solid volume fraction). The mechanical properties, such as substrate yield strength and adhesion, of wet flowable substrates vary depending on the substrate's volume fraction. The automatic mixer prepares the flowable substrates by slowly introducing solid particles to the desired amount of water while continuously mixing the combination. This method ensures uniformity in the substrate and its properties, enabling the systematic studies of amphibious fishes on mud of various wetness/strengths (**Fig. 7**, bottom left).

Li lab created an automated penetrometer system for characterizing mud based on its mud strength (**Fig. 7**, right). The penetrometer consists of a motor that drives a load cell attached to a flat, circular probe vertically into a mud sample. Based on the force readings sensed by the load cell at a given depth in the mud, we can determine the mud's volume fraction. A custom portable, hand-held penetrometer is available for mud characterization at any location. The lab also has a laser profilometer for measuring substrate surface deformations as well as a system for measuring surface drag forces. The Li group also built an automated horizontal drag force device that can measure forces in lateral and fore-aft direction using loadcells during the probe's extension and retraction for resistive force theory.

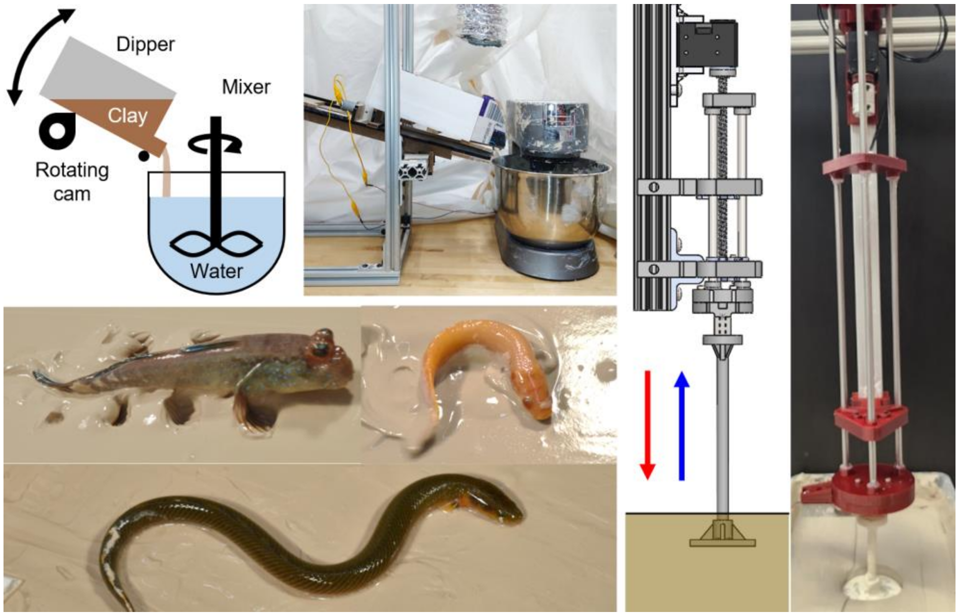

Fig. 7. Custom mud maker to create uniform mud of various wetness (various yield strengths) to study amphibious fish crawling, and custom penetrometer to characterize mud yield strength.

3.6. Custom terrain treadmill for studying complex 3-D terrain traversal at large spatiotemporal scales and high spatial resolution

We created a terrain treadmill to enable high-resolution observation of animal locomotion through large obstacles over large spatiotemporal scales (**Fig. 8**) of ~1000 cycles and body lengths. An animal (like a cockroach) moves through modular obstacles on an inner sphere, while a rigidly attached, concentric, transparent outer sphere rotates with the opposite velocity via closed-loop feedback to keep the animal on top. The high-resolution observation enables the study of diverse locomotor behaviors and quantification of animal–obstacle interaction.

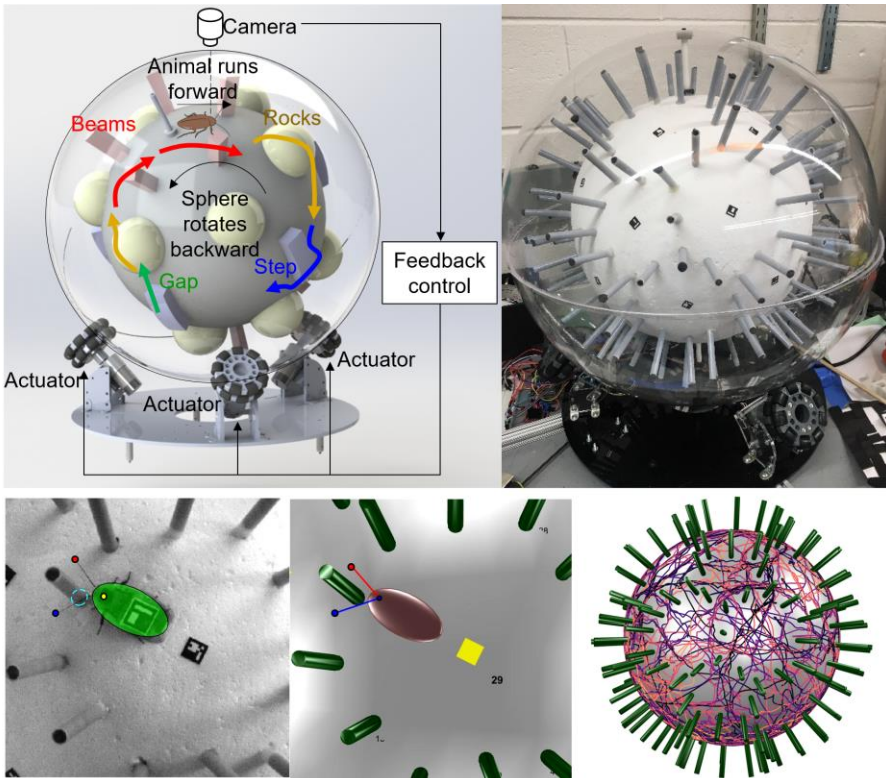

Fig. 8. Custom terrain treadmill enables high-resolution measurement of small animals over ~1000 cycles and body lengths.

This is the first ever laboratory platform for studying untethered animal locomotion through complex terrains at long spatio-temporal scales.

4. Robotic Physical Models for Studying Locomotion in Complex Terrains

The Li Lab has created many robots as active physical models for studying biological locomotion in complex terrains. Below are robots currently existing in the lab for ongoing research. We have the necessary facilities such as mechanical, electrical/electronic tools for creating new robots for studying novel biological questions.

4.1. Cockroach-Inspired Robots

We created multiple cockroach-inspired robots to understand multi-legged traversal and mechanical sensing of complex 3-D terrains with diverse types of large obstacles (**Fig. 9**). Some of them are robotic physical models, which generate relevant locomotor behavior using minimalistic design and actuation (**Fig. 9** top), well suited for discovering general principles, whereas others add degrees of freedom to be more biologically accurate but more specific to the animal being emulated (**Fig. 9**, bottom).

To traverse cluttered, large, deformable obstacles like grass-like beams, a hanging robot (**Fig. 9** top, middle) can generate forward propulsion and vertical oscillations to accumulate kinetic energy and passively rotate along its body roll and pitch directions.

An upgrade (**Fig. 9** top, right) further added control to the rotations. It is equipped with 2 custom 3-D force sensors and 72 pieces of touch sensors on the surface, which enables it to sense obstacle contact forces and torques. It can reach a sampling frequency of 50 Hz using a custom DAQ.

To traverse a horizontal, large, protruding obstacle like a bump or a horizontal, large, sagged terrain like a gap, a six-legged running robot with a tail (bottom, left) can accumulate large forward momentum from leg propulsion, and modulate its pitch rotation using its tail. To traverse a field of vertical, large, slim obstacles like a field of pillars, a six-legged running robot (bottom, second right) can change its shell shape. Finally, created a multi-functional six-legged robot (bottom, right) that overcomes multiple kinds of obstacles with human-involved control.

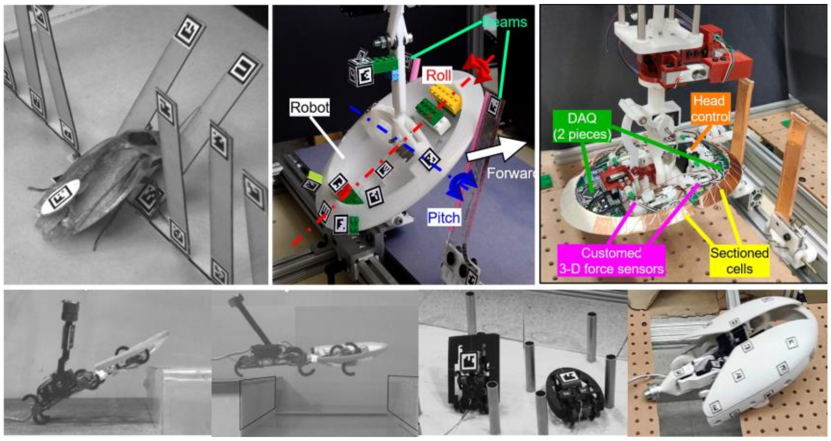

Fig. 9. Cockroach-inspired robots for studying multi-legged traversal and mechanical sensing of complex 3-D terrains with diverse types of large obstacles.

We also built cockroach-inspired robots to understand cockroaches' ground self-right **(Fig. 10)**. The robot has two wings that can open and close, and a heavy tail mimicking the cockroaches' waving legs to generate lateral oscillation.

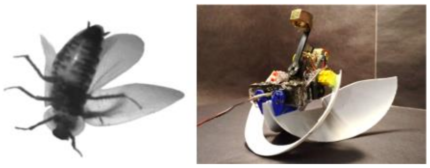

Fig. 10. Cockroach-inspired robot for studying ground self-righting.

4.2. Snake Robots

We created 2 snake robots to understand snake locomotion on a complex 3-D terrain (**Fig. 11**). Both robots have alternating pitch and yaw segments that allow 3-D bending. Both robots have Dynamixel motors to actuate each segment.

One of them is a one-directional wheeled snake robot with force-sensing-resistor sensors to sense contact forces from the obstacle-robot interaction (**Fig. 11**, top right). Its one-directional wheels allows generation of anisotropic friction coefficient (small in forward motion and large in backward and lateral motion) similar to that of snakes. It also has a suspension system that provides passive body compliance, similar to snake's passive body compliance, important for maintaining stability when moving in 3D.

The other is a sensorized snake robot, SenSnake, that can directly sense contact forces during obstacle interaction (**Fig. 11**, mid, bottom) in complex 3-D terrains. Each of the 12 body segments has 3 custom, low-cost, and flexible piezo-resistive sensors. The entire robot has 36 sensors that can be read at 30 Hz using a DAQ with a 32-channel multiplexer, which can also be

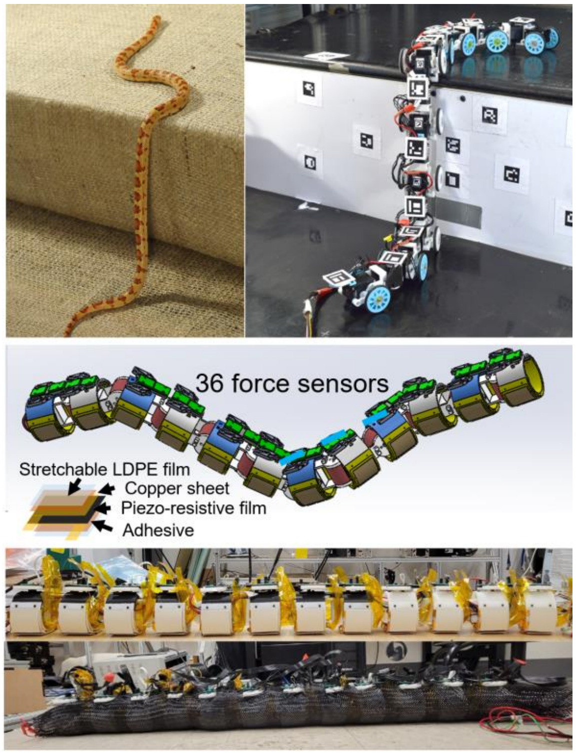

Fig. 11. Snake robots for studying limbless locomotion and mechanical sensing in complex 3-D terrains.

expanded to higher frequencies with purchase of additional multiplexers and DAQs. We also added a sleeve to SenSnake to reduce friction and prevent the gaps between the segments from getting caught on terrain edges.

4.3. Amphibious Fish Robot

We created a fish robot to study terrestrial locomotion strategies used by amphibious fish (**Fig. 12**). The robot has 10 body segments for lateral undulation and two fins with two degrees of freedom each to emulate fin shoulder and elbow motions. Amphibious fishes have 3 general strategies to move on land: using just their fins (e.g., **Fig. 12**, top left), using just body bending, and using body bending and fins together, (e.g., **Fig. 12**, top right). We can control the robot's lateral undulation and fin actuation to generate various gaits that fall under the three general strategies. Body and fins are actuated using servos motors. The robot is water-proofed from the bottom and sides, so it can run over wet substrates such as mud. The robot is also equipped with 2 current sensors to measure its power consumption at a rate of 50 Hz.

Fig. 12. Fish robot for studying amphibious fishes crawling on mud.

4.4. Spider Robots

We created two spider robotic systems for studying vibration sensing and locomotion of spiders on webs.

The first is a robophysical model of a spider-prey system on a web to study how spiders can process signals from prey through the web (**Fig. 13**). The spider-web-prey system is built with 80-20 bars on a ceiling. The robophysical model consists of a spider robot, prey robot, and a model web system and can conduct multiple simultaneous measurements during experiments.

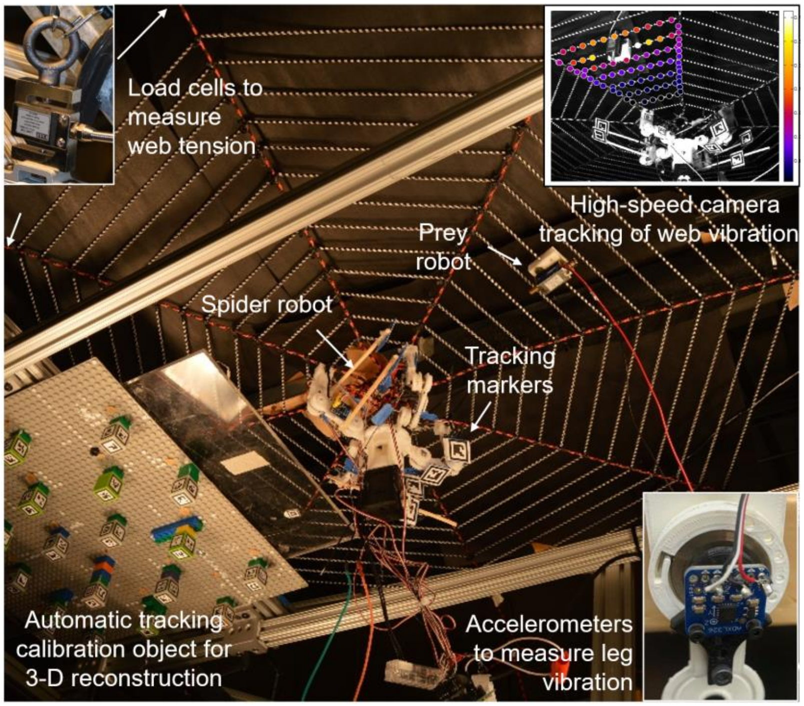

Fig. 13. Spider-prey-web robotic physical model for studying spider's vibration sensing on a web to detect prey.

The spider robot is a PLA 3D printed structure with torsional springs for joints, along with a motor (Dynamixel XM430-W350-R, ROBOTIS, Lake Forest, CA, USA) to actuate the spider robot to do a crouching motion. The spider robot has 8 ADXL 326 accelerometers on each joint. We use 2 USB-231 MCC DAQs connected to the accelerometers to measure the vibrations of the spider robot's joints. BEEtag markers can be attached to measure the orientation of the spider's body. The prey robot is a simple linear solenoid attached to the web through PLA 3D printed structure with teeth that are clamped on to ensure the prey robot is securely fastened onto the web. It is controlled through an Arduino UNO that is connected to a L298N motor driver.

We also measure the vibrations of the web, made from shock cords and paracords with qualitatively similar viscoelastic properties and geometry to that of a spider web. Two high speed cameras (Photron Fastcam Mini UX-100, 1024 x 1024 pixels @ 4000 fps) record the vibration of the web. There are many lamps to ensure proper lighting for the setup. For calibration, we use a calibration object with BEEtag markers using Lego bricks (The Lego Group, Billund, Denmark). The high-speed camera tracks individual points on the striped web to measure the web vibration, in which the Fourier Transform is applied to gather the magnitude of certain frequency components. 8 Load Cells (S Type Load Cells DYLY-103) are used to measure web tension. The entire system is triggered via a RW Electronics Standard Trigger Box that sends a rising edge signal to both cameras and both DAQs to trigger the prey and spider robot actuation and data collection.

The second is a spider robot with eight legs inspired by orb-weaver spiders to understand how they move on the web (**Fig. 14**). Each leg is actuated by 3 DYNAMIXEL XL330 motors, allowing the gripper to move in 3-D space. It is also equipped with 1 Atlas Hyperion DS11SCB Digital Servos on each leg that actuate claws for the spider robot to hook onto the web. The robot is controlled using an Arduino Nano and has an absolute orientation sensor to control to allow the spider to orient itself on the web. We created an artificial web similar to a spider web made from paracords and shock cords (**Fig. 14,** right). With manual control, the spider robot could move on another artificial web.

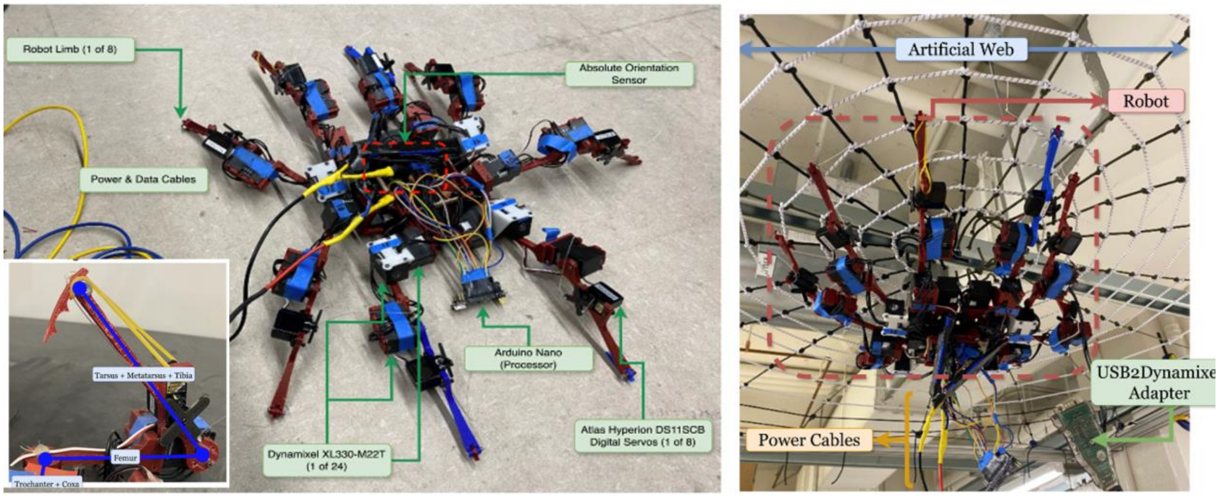

Fig. 14. Spider robot for studying spider locomotion on a web.

4.5. Quadrupedal Robot with 3-D Flexible Spine

We created a quadrupedal robot with a 3-D flexible spine to study the climbing motion of mountain goats (**Fig. 15**). The robot has 4 legs with 3 degrees of freedom per leg. Its spine has 3 degrees of freedom and can bend along pitch, roll, and yaw directions (**Fig. 15**, bottom). The robot can not only use standard quadruped gaits (**Fig. 15**, top right), such as walking and running, but can also achieve more diverse, novel gaits such as those observed in mountain goats spreading its four legs while bending its body to gain footholds against precarious, steep mountain terrain (**Fig. 15**, top left vs. bottom). We are also developing high-resolution force sensors that can detect normal and shear forces when the legs grip a surface to be embedded into robot feet inspired by mountain goat hoofs. We will mount these sensorized feet to the robot.

We are using this robot to study highly unstable locomotor transitions that involve such novel use of the body and legs and how tactile sensing and proprioception can help feel the terrain to ensure stable foothold as well as allow transient yet crucial force generation such as thrusting, braking, etc.

4.6. Vine-Inspired Soft Robot for Studying Growth into Dense Rubble

We created a low-cost, soft, continuum vine robot growing into an earthquake rubble analog (**Fig. 16**, left). The vine robot consists of a base chamber (white) and three independently actuated pneumatic muscle bundles (red). The earthquake rubble is made of bottled water. The bottled water can be bundled together and used in combination with plates and beams to emulate less cluttered parts of earthquake rubble, or they can be used alone and without bundling to emulate extremely cluttered parts of earthquake rubble (**Fig. 16**, right).

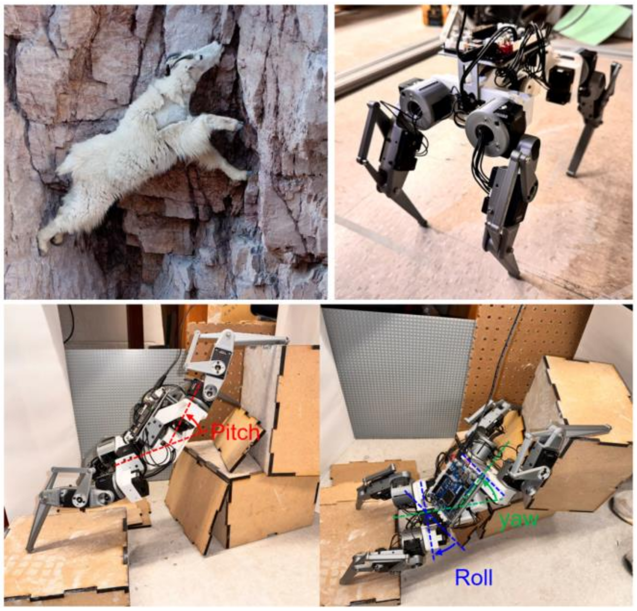

Fig. 15. Mountain goat-inspired quadrupedal robot for studying how to move over steep mountain terrain using novel locomotor gaits and transitions far away from near-steady-state walking and running.

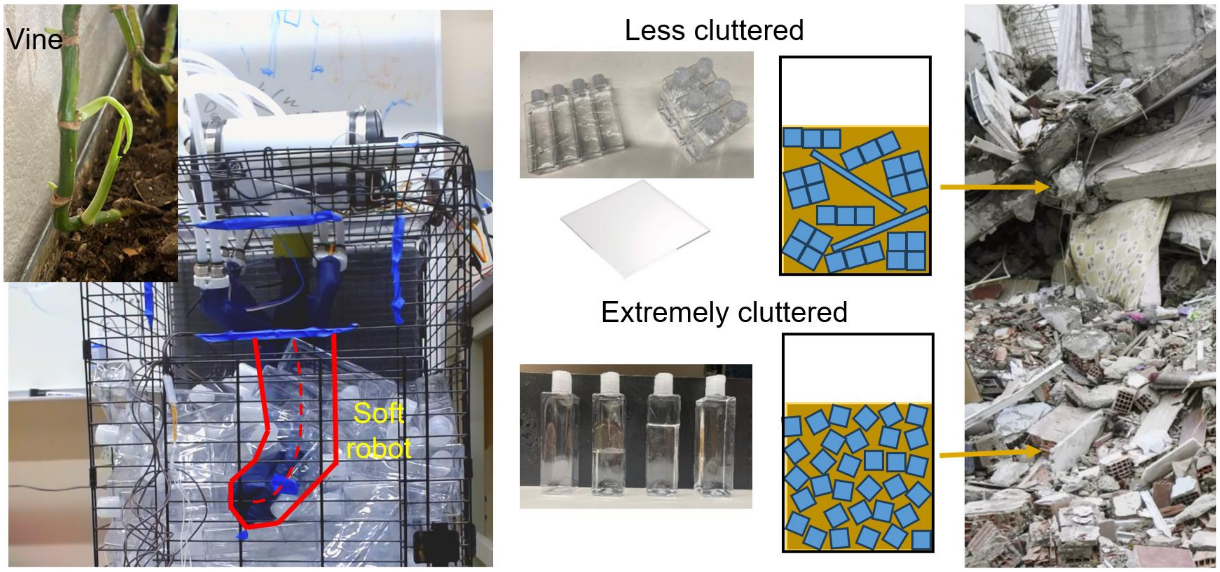

Fig. 16. Vine-inspired soft robot for studying growth into dense rubble created by bottled water and plates in various clutter levels.

5. Computer Equipment

5.1. Experimental Workstations

For high-speed imaging, motion tracking, and 3-D reconstruction, the Li lab custom built five high-performance experimental workstations:

- One 64-bit operating system, Intel Xeon E5-2667 2.90 GHz 16 Cores/32 Threads, NVIDIA GeForce GT 710, 32 GB RAM, 20.25 TB SSD RAID, 3x BitFlow Claxon-CXP4 Quad CXP-12 Frame Grabber, and 24x Samsung 870 EVO 500G SSD
- One 64-bit operating system, Intel Core i7-6800K 3.40GHz, NVIDIA GeForce GT 710, 64 GB RAM, 8 TB SSD RAID, 2x BitFlow Claxon-CXP4 Quad CXP-12 Frame Grabber, and 16x Samsung 870 EVO 500G SSD
- One 64-bit operating system, Intel Core i7-5820K 3.30GHz, NVIDIA GeForce GTX 1070 Ti, 32 GB RAM, and 8TB SSD RAID
- Two 64-bit operating systems, Intel Core i7-5820K 3.30GHz, NVIDIA GeForce GT 1030, 64 GB RAM, and 8TB SSD RAID

5.2. Computation Workstations

For simulation, we custom built three high-performance computational workstations for multi-thread computation:

- 2 AMD Threadripper 1950X 16-core/32-thread CPU computers, NVIDIA GeForce GT 1030, 32 GB RAM, 8TB storage (**Fig. 17**)
- 1 AMD Threadripper 2990WX 32-core/64-thread CPU computer, NVIDIA GeForce GT 1030, 32 GB RAM, 8TB storage

Fig. 17. 16/32-core computation workstations.

5.3. General Use PCs and Laptops

Distributed in the lab spaces are 8 Windows and/or Ubuntu desktops for general research purposes. There are also 3 laptops, all with software all with software capability for controlling mobile automated systems. For data storage and backup purposes, there is 1 Synology server with 50 TB of space (can be expanded to 192 TB with the purchase of additional hard drives) as well as over 100 TB of external hard drives.

5.4. Software

The Li group has the following software:

- Imaging: StreamPix 7, Fastec FasMotion, Photron Fastcam, NorPix Batch Video Processor
- CAD: SolidWorks 2021
- Circuit design: EAGLE
- Data acquisition: LabVIEW, MATLAB
- Data analysis: JMP Pro, MATLAB, Mathematica, ImageJ, Python, DeepLabCut, dltdv8a
- Automated System Control: Arduino IDE, VS Code, MATLAB
- Other common office and engineering software provided by Johns Hopkins University and Whiting School of Engineering
- Simulation: Project Chrono Engine, POV-Ray, ANSYS, Visual Studio, CMake, MATLAB

6. Shared Facilities and Resources Li's Lab Can Access

Dr. Li's group has access to the following shared facilities and resources:

6.1. JHU Laboratory for Computational Sensing & Robotics "Robotorium"

- 2,500 sq. ft. shared space
- shared graduate student and postdoc offices
- shared work benches
- a small NC machine shop

- a Stratasys F170 3D printer
- 2 Sun 16-core/32-thread CPU computers, 16 GB RAM, 300GB storage
- 1 Dell 16-core/32-thread CPU computer, 16 GB RAM, 20TB storage
- 1 Penguin 20-core/40-thread CPU computer, 128 GB RAM, 4 NVIDIA Titan Black GPUs, 12TB storage

6.2. JHU Whiting School of Engineering Advanced Manufacturing Facility

- Eight Universal Robotics UR5/UR5e robotic arms
- 3-D printing: 2 Stratasys uPrint SE Plus, 2 Startasys F370 with multi-material printing
- Laser cutting: 2 Universal Laser VLS 60
- CNC milling: Fadal VMC 3016 Milling machine
- Machining: waterjet cutting, mills, lathes, drill press, grinder, sander, press, vertical bandsaw, hand tools
- Other services: coatings and heat treating, tube bending, machining close tolerances, woodworking, precision grinding, TIG and MIG welding, braising, forklift and rigging, assembling, inspection
- mechanical fabrication services and consultation
- student makerspace

6.3. Department of Materials Science and Engineering Facility

- 2 rheometers to measure viscosity and viscoelastic properties
- ARCH, a shared computing facility, with a rockfish cluster of over 34,368 cores, linked via optical fiber to high performance computing

6.4. Maryland Advanced Research Computing Center (MARCC) Clusters

- Maintained by JHU and Univ. of Maryland College Park
- Over 23,000 cores and a combined theoretical performance of over 1.4 PFLOPs
- Combination of Intel processors and several NVIDIA K80/P100 GPUS
- 14 PB ZFS storage on Linux

6.5. Shared Personnel Support

- Department of Mechanical Engineering and Laboratory for Computational Sensing and Robotics (LCSR) offers research support, including but not limited to accounting, property management, and procurement.
- LCSR has several full-time computer and electrical engineers who can offer technical advice and support on computing, electronics, mechatronics, and automation.