A Novel Terrain Treadmill to Study Animal Locomotion in Complex 3-D Terrains

LCSR REU Final Report
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Abstract:

A major challenge to understanding terrestrial locomotion in complex natural terrain is the lack of tools to perform controlled, systematic experiments in the laboratory. Recent progress was made by creating complex 3-D terrain arenas of obstacles such as grass-like beams with controlled and variable geometry and stiffness. However, these terrain arenas only allow experiments at relatively small temporal and spatial scales (~10 stride cycles, ~10 body length) with low resolution observations (~5% pixels representing the animal). Here, we create the first terrain treadmill to enable high resolution observations of locomotion in complex 3-D terrains over a long time and a large distance, analogous to treadmills for studying continuous running and walking on flat, rigid ground. Our terrain treadmill consists of two rigidly attached concentric spheres. The animal moves through...
modular terrain on the inner sphere, while the transparent outer sphere allows its position to be tracked in real time. This is then used to rotate the spheres opposite to the animal via closed-loop control to keep it on top. To demonstrate the usefulness of our device, we tested its performance in eliciting sustained locomotion of the discoid cockroach through cluttered pillar obstacles. In a single, continuous trial, the animal moved through pillars for 25 minutes (2500 stride cycles) over 100 m (2000 body length). For 99.7% of the experiment, the terrain treadmill contained the animal within a 5 cm² region even at locomotion speeds of up to 10 body length/s, enabling high resolution observations (25% pixels representing the animal). Our terrain treadmill not only increased limits of experiment duration (by 250×), distance (by 200×), and resolution (by 5×), but is also opening doors to studying sensorimotor control in complex terrains.

(Note: the preceding abstract was submitted to the Society for Integrative and Comparative Biology Annual Meeting 2018, awaiting acceptance)

**Introduction:**

Researchers around the world have ambitious visions for the future of robotics. Robots have the potential to impact an incredibly wide variety different areas from health care, to search in rescue, to extraterrestrial exploration. Existing robots have been designed and built to run, swim, and fly through our world. Unfortunately, up to this point, these behaviors have been predominantly limited to highly controlled, lab based settings. When some of the most advanced robots are moved out of the lab and into real environments, most fail to accomplish seemingly simple tasks. Naturally, some of the most beneficial applications for robot use are in highly unpredictable and often dangerous settings. Therefore, researchers around the world are tasked with the problem: How do we design robots that can move and adapt in a chaotic world?

The Animal Kingdom provides an amazing source of inspiration for robotics research. Animals are capable of incredible feats of mobility and skill in almost any terrain on earth. Cockroaches, in particular, are very skilled at maneuvering in hard to reach places. Consequently, they also offer a great opportunity to study animal locomotion through highly complex and varied terrain.

**Problem Statement:**

A major challenge to understanding cockroach locomotion in complex terrain is the lack of tools to perform controlled, systematic experiments in the lab. Recent progress was made by creating complex 3-D terrain arenas of obstacles such as grass-like beams with controlled and variable geometry and stiffness. However, these terrain arenas only allow experiments at relatively small temporal and spatial scales with low resolution observations. The purpose of this project is to develop the first terrain treadmill to enable high resolution observations of cockroach locomotion in cluttered 3-D terrains over a long time and a large distance.
**Procedures:**

The terrain treadmill consists of a smooth, clear outer shell mechanically coupled to a solid inner sphere using a rigid rod. The surface of the inner sphere contains obstacles of various types. These obstacles mimic objects that a cockroach might encounter out in the real world such as rocks, twigs, or even blades of grass. The two spheres are placed on a structure containing three wheels which are controlled using motors. The orientation of these wheels allow the ball to be actuated in any direction based on the relative angular velocities between them. A cockroach is placed on the very top of the solid inner sphere and is tracked using a camera.

**Manufacturing**

The outer shell is composed of two smooth acrylic hemispheres which were custom ordered with a 24-inch diameter. These hemispheres needed to be joined together to form a solid sphere while minimizing any outer protrusions or obstacles which may have obscured the cockroach from the camera. To do this, thin, clear tape is used to join the pieces together. Then, a rod is placed in the center to clamp the two halves together.

The inner sphere is a 16-in Styrofoam ball. A plastic rod was tapped on both ends was passed through the center of the sphere. The sphere is then fixed in the center of the rod using shaft collars on both sides. Finally, the rod and Styrofoam sphere were suspended inside the acrylic hemisphere using bolts through holes in the center of each hemisphere.
The last aspect of the device consists of three motors mounted on a base. These motors use Omni-directional wheels which are capable of rotating like a normal wheel but also contain rollers which slide in the perpendicular direction. The motors are equally spaced around the base and tilted to 45 degrees. This angle allows the wheel to be tangent to the sphere at the point of contact, which reduces vibrations and simplifies the kinematics I discussed earlier.

![Figure 6](image)

**Figure 6** (a) Apparatus base (b) Motor angle (c) Omni-directional wheel

**Software**

The device uses a computer running Robot Operating System to handle image processing, control, and data collection. In the first step, an image is taken from the tracking camera. This image is used to track the cockroach position in real-time using an Aruco-Tag. Aruco-Tags are VR tags which can be used to track 3-D position and orientation information using only one camera.

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Next, the position data is filtered using a constant velocity model Kalman filter. This is a statistical filter which uses previous measurements and measurement uncertainties to more accurately predict the tag position given noisy measurements. The filter can also be used to estimate the animal position when the animal is partially obscured by obstacles and tracking information becomes unavailable.

This filtered position is sent to a high-level PID position controller. The error for the controller is the position of the cockroach relative to the center of the frame. The purpose of this controller is to calculate the control effort required to keep the animal centered on top of the ball.
After the control effort is calculated, it is passed through the forward kinematics for the device. These are the set of equations that convert control effort from real-world coordinates \((x, y, \theta)\) into desired velocities for each of the three motors which actuate the ball.

\[
\begin{align*}
  v_{s1} &= -v_y \cos \phi + K_z \omega_z \\
  v_{s2} &= \left\{ +\left(\sqrt{3}/2\right)v_x + \left(1/2\right)v_y \right\} \cos \phi + K_z \omega_z \\
  v_{s3} &= \left\{ -\left(\sqrt{3}/2\right)v_x + \left(1/2\right)v_y \right\} \cos \phi + K_z \omega_z \\
  K_z &= -R \sin \phi
\end{align*}
\]

(Figure 5 Forward kinematics\(^1\))

Finally, the desired velocities are sent from the computer to an Arduino microcontroller. This microcontroller is running three PID velocity controllers which use encoder information from the motors to match the desired velocities for each motor. The microcontroller also sends the actual motor velocities back to the computer for data analysis.

**Analysis of Data:**

After building the device, we tested its performance in eliciting sustained locomotion of the discoid cockroach through cluttered pillar obstacles. Data was collected using Robot Operating System. This included camera recordings, tag positions, and actual motor velocities.

In a single, continuous trial, the animal moved through pillars for 25 minutes (2500 stride cycles) over 100 m (2000 body length). For 99.7% of the experiment, the terrain treadmill contained the animal within a 5 cm\(^2\) region even at locomotion speeds of up to 10 body length/s, enabling high resolution observations (25% pixels representing the animal).

(Figure 6 Terrain Treadmill tracks cockroach during (a) free locomotion, (b) approach, (c) traversal, (d) escape, and (e) free locomotion)
Conclusions:

Our design provides a configurable platform for high resolution videography of body, leg, and antenna movement and interaction with terrain. In preliminary experiments, it not only increased limits of experiment duration (by 250×), distance (by 200×), and resolution (by 5×), but is also opening doors to studying muscle activation and neural control on the “tethered” animal moving in complex environments.

References:


Appendices:

Research Ethics

Over the course of the program much thought was given to the potential impact of various projects in the lab, and steps were taken to guide the projects in directions that would most benefit society through the advancement of biology, engineering, and robotics. Also, great care was taken to maintain the privacy of ideas, designs, and data until formal publications had been made.

Value of the Program

Throughout the process of building this apparatus, I gained a large amount of technical knowledge regarding programming, electronics, and manufacturing. I found it very valuable see the project from start to finish from the initial design phase to preliminary data collection. Furthermore, I learned many insights into research in an academic setting from being completely immersed within the lab for the last three months.

Overview of the Program

I greatly enjoyed most aspects of the program. My project was unique, challenging, and exciting. I felt that I was able to produce work that will benefit my own lab as well as the greater research community in the future. The program directors were very accommodating to my schedule which differed from most other students. Furthermore, I really enjoyed the field trips that we took throughout the summer.