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Citation	
Version Type	VoR
URL	https://doi.org/10.18910/84885
rights	
Note	

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Development of a sensorized snake robot to study limbless locomotion in complex 3-D terrain

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1 Introduction

Generalist snakes can quickly and stably traverse complex 3-D terrain with many large obstacles, presumably by using sensory feedback control to generate appropriate propulsive forces distributed along its body. Despite similar morphologies, snake robots are far from being good at traversing complex 3-D terrain cluttered with large obstacles. Many current robots use vison to scan the environment to plan motion using terrain geometry [1]. Some robots use methods like passive mechanical compliance [2] and control compliance [3] that allow the robot body to try to maintain contact, but it is still unknown on how to deform the body to push against the obstacles to generate the right forces in response to the terrain contact. Most of these methods result in the robot moving slowly or slip substantially. Understanding how snakes sense and control physical interaction with obstacles to generate effective locomotion is not only important for biology but will also advance robotics. However, the force sensing modality of snakes are poorly understood. To begin to fill this gap, here we develop a sensorized snake robot instrumented with low-cost, flexible, piezoresistive sensor arrays to measure normal contact forces along the body.

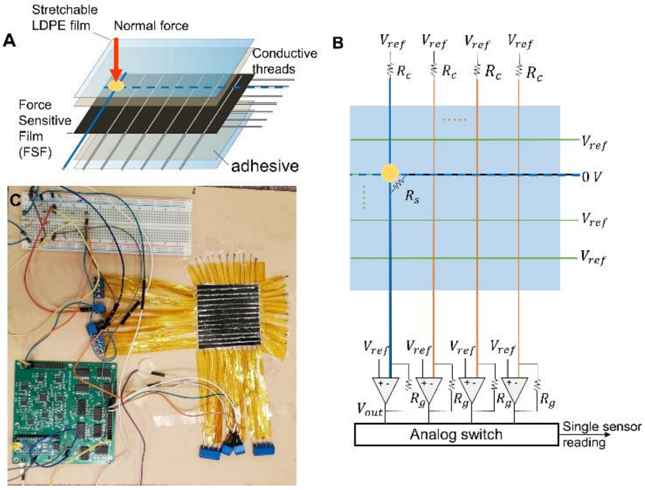

Figure 1: Piezoresistive Sensor Array and its working principle. (A) The distributed piezoresistive sensor array sensing an applied normal force (yellow circle). (B) Working principles of the sensor array and its electrical-grounding-based signal isolation circuit [5]. (C) The sensor array with only 4 rows and 4 columns are connected to the DAQ board.

2 Methods and Results

To detect contact forces throughout the entire length of the robot body, we adopted a flexible and low-cost distributed force sensor array design initially created for a tactile glove for human and robotic grasping applications [4]. This sensor array consists of three layers (Figure 1A). A row and column of conductive threads are placed orthogonally on either side of a piezo-resistive film, creating a grid of individual sensors where row and column threads overlap. When a normal force is applied on an individual sensor (Figure 1B), there is a change in resistance. Each sensor's resistance is estimated with a DAQ board, which can in turn be used to estimate the applied force using the following equation [6]:

$$R_s = (mF + b)^{-1} \tag{1}$$

where R_s is the resistance of the sensor, F is the applied force, and m and b are the fitting parameters.

As a proof of concept, we first integrated the sensors into a 7-segment robot prototype. 72 sensors were placed at the bottom of the middle segment of the prototype (Figures 2A-C). This prototype was then tested to see whether the sensors can detect contact forces when the robot laterally undulated on a flat ground and on rubble of blocks (Figures 3A-B). From the results we found that when the robot is stationary for the first 12 s, the forces estimated remain constant. Once the robot starts moving, there is a change in force seen regularly on flat ground (Figure 3C) and at not so regularly on a rubble of wooden blocks because the robot is not regularly in contact with the blocks unlike the flat ground (Figure 3D).

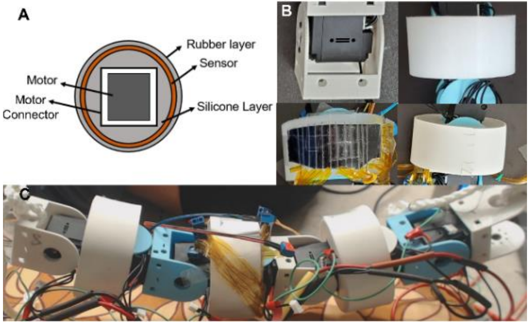

Figure 2: Robot prototypes. (A) Cross-section of the robot with different layers to assist sensor integration. (B) A silicone layer is added over the motor connector to allow passive deformation during interaction with sharp edges and corners of obstacles to improve contact. A grid of sensors are placed over the silicone layer and a rubber layer is placed over the sensors to prevent wear and tear. (C) First 7-segment prototype with sensors integrated.

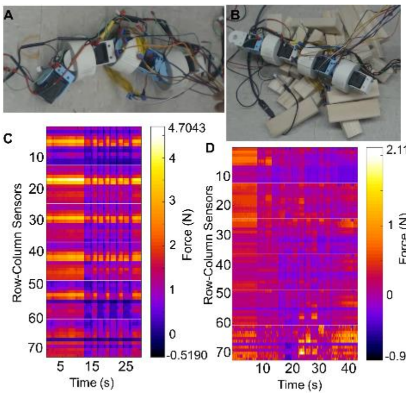

Figure 3: Detection of contact forces by sensors during robot motion. (A) Lateral undulation on flat ground. (B) Lateral undulation of on rubble of wooden blocks. (C) Force color map from lateral undulation on flat ground. Each row corresponds to a sensor with force detected at each time stamp. (D) Force color map from lateral undulation on rubble of wooden blocks. Each row corresponds to a sensor with force detected at each time stamp. The last few sensors have more noise due to loose contact since the cables were not packaged well.

Next, we developed a revised robot prototype to better integrate the sensors on the robot and increased the number of segments to 12 since the first prototype is too short to help the body to move over a complex 3-D terrain (Figure 4D). Gaps between each segment were also reduced to prevent the robot from getting stuck over the obstacles during locomotion in complex 3-D terrain. For a 12-segment robot of the first protype there would be a total of 864 sensors with a sensing frequency of 6 Hz. Hence, we decreased the number of sensors to 100 sensors to increase the sensing frequency to 16 Hz. To use this robophysical model to understand how animals utilize contact forces during locomotion in complex 3-D terrain, we built a simplified terrain with height of each block varying in only the forward direction (Figure 4A). To demonstrate how the sensing works, we collected readings from the sensors while pitching down one robot segment (Figure 4A, red circle). A change in force was detected on the sensors installed on the segment pushed against the terrain (Figure 4C, orange regions).

3 Future Work

Currently we are working on replacing the calibration method using Eq. 1 with a model that would help us to accurately estimate the force [6]. We are also modifying the revised prototype by replacing the silicone layer with a lightweight material that would help the robot move well in a complex terrain. We are also planning on using a sheet sensor array to increase the area of force contact while maintaining the number of sensors on the robot. We plan to use our sensorized robot to perform systematic experiments to understand the principles of how to control body deformation and terrain contact to generate forces while maintaining stability. This will not only be informed by, but also help us understand animal observation. Once we obtain a better understanding of how contact forces relate to body configuration and motion, we plan to develop sensory feedback control strategies for the robot to move over more complex 3-D terrain similar to snakes (see other poster by Fu, Astley, Li, Snakes traversing rubble-like terrain). Finally, we are also developing a sensorized complex terrain platform to measure distributed contact forces in snakes.

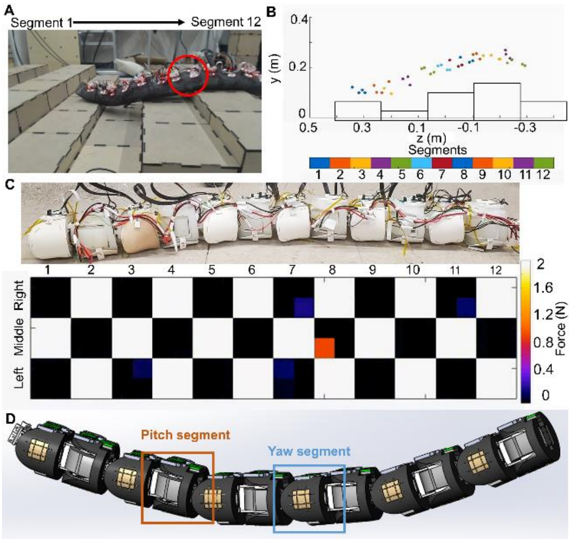

Figure 4: Robot on the simplified terrain. (A) Sideview of the robot on the simplified terrain with the 8th segment in red circle pushing against the terrain. (B) Visualization of positions of LED markers tracked by a motion tracking system. (C) Detection of forces on the 8th segment pushed against the terrain. Each block in the colormap corresponds to the 4 sensors placed on each segment. (D) Revised 12-segment prototype with 4 sensors on each side of each yaw segment and 4 sensors at the bottom of each pitch segment.

4 Acknowledgements

This work is supported by Burroughs Welcome Fund through the Career Award at Scientific Interface, Johns Hopkins University through the Catalyst award and the Arnold and Mable Beckman foundation through the Beckman Yong Investigators Program. We thank Nikhil Murty for the pre-liminary work.

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