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SquMA Bot: Foam Squishable Motor Actuated Robot

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1 Introduction

Animals live in complex and unpredictable environments and must be able to continuously adapt their locomotion. Some of the most diverse and adaptable animals are composed of soft deformable materials [2,3]. One example is the caterpillar, which is the larval stage of many moths and butterflies. They exhibit a wide range of gaits from the crawl of the Tobacco hornworm (*Manduca sexta*) to the inching of the Winter moth (*Operophtera brumata*) (Fig. 1B). Our lab uses caterpillars model system for soft bodied robots because they have evolved to occupy almost every environment on earth, have a completely soft body, and rely on a muscle tendon system rather then a hydrostatic one.

In soft robotics, one of the major challenges is the actuation system. Most soft robots are limited in that they rely on either an off-board or low force actuation system [3]. Widely adopted methods of actuation include using sensitive compressors to inflate chambers within the robot [4–6] or shape memory alloys (SMAs) that require a great deal of electrical current and do not produce large deformations [7–9] or high force. Other motor tendon robots are made with non-compressible elastomers which limits deformability [10]. There is a need for a robust on-board actuator system capable of high force outputs and large deformations.

In this paper we describe a foam bodied robots driven by a motor tendon system (Fig. 1A). The body design, kinematic comparison, and possible future applications will be the primary focus of this paper. Using highly deformable foam allows for both compression and bending with seamless gait transitions. Our prototype demonstrates the effectiveness of this method.

2 Design and Development

The design of this robot is based on the tubular elongated body of *Manduca sexta*. We modified the cross-section to be triangular for increased stability, a larger ground contact area, and lower center of gravity. This design takes advantage of two effects, frictional interactions with the ground and viscoelastic expansion from compressed polyurathane foam. The 3D printed end caps are designed to be low friction in the forward direction, and higher friction in the reverse direction. Similarly, the polyurathane midsection is lifted off the surface to enable a forward sliding motion.

The body design is split into three subsections. These sections are designed to reflect different aspects of caterpillar motion - arching (Fig.1A), contracting, and lifting or rearing. The red end caps (Fig.2A.3 and 2A.8) are designed to either compress the entire robot or bias the system by compressing one side preferentially to create lifting and turning motions. The mid sections are designed with both a biased compression zone (Fig.2A.10), to force the section upward into an arching motion, and a high compression zone (Fig.2A.1) to give the robot a larger step.

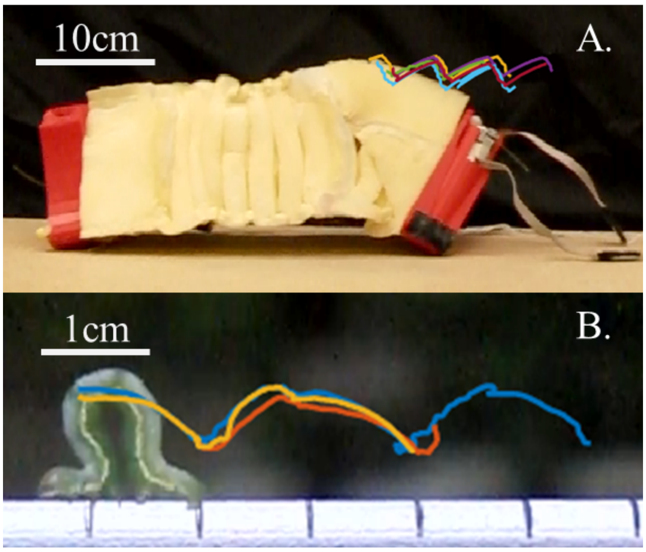

Figure 1: Kinematic comparison. A) Kinematic trace at peak of arch in SquMA Bot. B) Kinematic trace at peak of arch in *Operophtera brumata*. Different colors represent different trials of the same individual

The locomotion of the robot is dictated by the compression and recovery properties of the foam. In this prototype we choose a soft polyurethane foam (FlexFoam-iT III, *Smooth-ON Inc., Macungie, PA*) for its high deformability and ease of manufacturing. The stiffness of the foam resists the contraction of the body while its subsequent relaxation produces the locomotive force. We determined the stiffness of the foam by compressing samples to 30 percent of the starting thickness on an Instron (*Illinois Tool Works Inc, Norwood. MA*). The stiffness of the foam is independent of strain rate within the regime this robot operates in (Fig.2B). As gases escape the foam matrix, the stiffness of the material approaches that of bulk polyurethane. We will also show that recovery speed depends upon the volume of air required for restoration. Larger samples need to take in more air to fully recover compared to smaller samples. This implies that smaller robots may move at higher relative speeds than larger robots. Such a hypothesis is basis for future work.

3 Performance

We characterized the performance of the robot through video analysis to compare its kinematics to that of the caterpillar Winter moth, *Operophtera brumata* native to Costa Rica (Fig.1A). The robot also navigated a terrestrial obstacle course to demonstrate its adaptability to an dynamic setting (Obsticle Course Performance: http://tinyurl.com/thefoamrobot).

When analyzing the behavior of the Winter moth

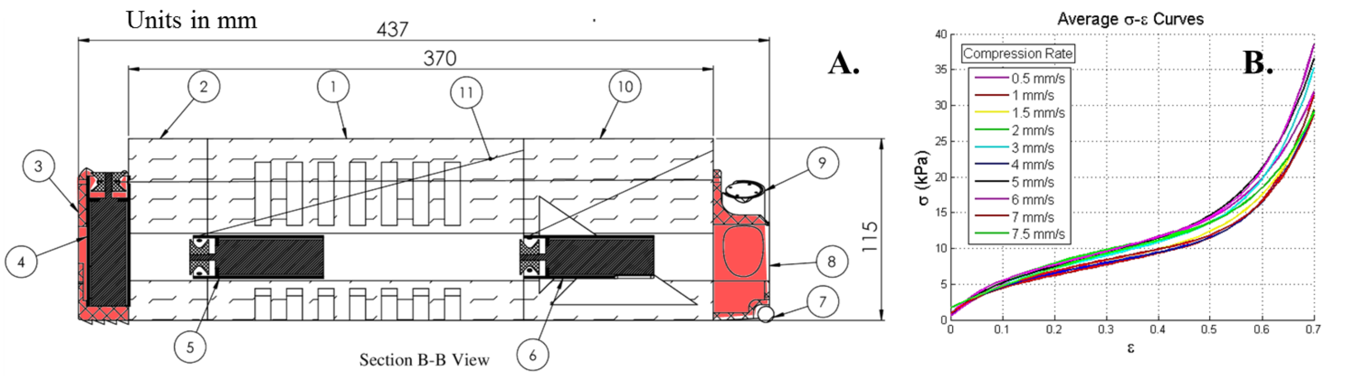

Figure 2: A) Schematic of Robot. 1) High Compression Section. 2) Limited Compression Section. 3) Lifting Motor Front Cap. 4) Lift Motor Assembly. 5) Compression Motor. 6) Arching Motor. 7) Directional Friction Roller. 8) Turning Motor Rear Cap. 9) Turning Motor. 10) Arching Section. 11) Kevlar Tendon Paths. **B) Compression Curves of Foam Body.**

and we found a highly stereotyped gait pattern (Fig.1A). Each cycle of inching is comprised of six steps. 1) The animal is extended and griping with the front thoracic legs and rear prolegs. 2) The prolegs release their grip. 3) The midsection begins to arch upwards, drawing the prolegs closer to the thoracic legs. 4) Once the prolegs reach the thoracic legs they re-grip the substrate. 5) The animal then releases the thoracic legs. 6) Finally, the body elongates with the anterior end moving forward until the starting body posture is reached, restarting the cycle.

Similarly, the robot also follows a 6-step gait pattern (Fig.1B): 1) The robot is extended with the head region flat on the substrate to create a high friction area. 2) The rear high friction region is released by beginning to arch the body. 3) The body is fully arched, bringing the rear region forward. 4) The rear high friction region is engaged. 5) The head is then angled to release the high friction front grip. 6) Lastly, the body is relaxed, pushing the front region forward to the initial posture.

4 Discussion

The inspiration for our design was drawn from caterpillar's soft body, inching gait, and tendon-driven actuation. Caterpillars are almost entirely soft and have infinite degrees of freedom, yet they are able to produce a wide repertoire of repeatable motions. This robustness relies on the morphology of the animal as well as the material properties of their bodies. Our robot was able to replicate the inching gait using a tendon-driven system while maintaining compliance.

In future prototypes, we intend to replace the 3D printed plastic end caps with molded foam. The foam end caps would be slightly stiffer than the rest of the body, but would still be flexible. Another future goal is the inclusion of a interchangeable "tool module" located at the front of the robot. A tool would allow individual robots to accomplish different functions. The motor-tendon and foam platform is also capable of scaling to smaller and larger sizes with minimal modification to the design or control system.

This system can be easily modified to create an entirely on-board actuation system - eliminating the need for a tether. This differentiates our design from many other soft robots that rely on pneumatic systems that generally require a tether - limiting their autonomy. This makes the motor-tendon actuation and foam platform a good candidate for long term exploration and search and rescue missions, where a tether could be caught or damaged by the terrain.

Due to the low cost, ease of manufacture, and autonomy, many units would be able to work together in a distributed network of sensors (camera, chemical sensor, GPS, etc.), and manipulators (grasping, drilling, cutting, etc.) to accomplish complex tasks. By distributing the components and scaling individuals in size, we will be able to exploit the design advantages and minimize design drawbacks such as slower speed or payload capacity when compared to rigid wheeled devices.

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