Soft Foam Robot with Caterpillar-Inspired Gait Regimes for Terrestrial Locomotion

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**Recommended Citation**  
C. M. Donatelli et al., "Soft foam robot with caterpillar-inspired gait regimes for terrestrial locomotion,"  
*2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS),* 2017, pp. 476-481,  
[https://doi.org/10.1109/IROS.2017.8202196](https://doi.org/10.1109/IROS.2017.8202196)
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Soft Foam Robot with Caterpillar-Inspired Gait Regimes for Terrestrial Locomotion

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Abstract—Caterpillars are the soft bodied larvae of lepidopteran insects. They have evolved to occupy an extremely diverse range of environments and to locomote in complex three-dimensional structures without articulated joint or hydrostatic control. These animals make excellent bio-inspiration for the field of soft robotics because of their diversity and adaptability. In this paper, we present SquMA Bot, a caterpillar-inspired soft robot. The robot’s body is primarily composed of a soft viscoelastic foam, and it is actuated using a motor-tendon system. SquMA Bot is able to mimic the inching gait of a caterpillar and can use its flexible body to adapt to a range of environments. This bio-inspired prototype demonstrates the effectiveness of a soft robot as a potential tool for exploring environments too dangerous for humans.

I. INTRODUCTION

Traditional robots in industry, medicine, and research are based on well described rigid body models and designed to be effective and efficient at a specific task. A drawback to this approach is that such specialized designs are not necessarily adaptable in a changing environment and robots constructed of hard materials can be dangerous when interacting with humans or in other natural settings. The devices work largely in a carefully controlled environment limiting their robustness and broad deployment. The nascent field of soft robotics has made great advancements to address some of these limitations, often drawing inspiration from biological systems. Our work is inspired by the remarkable flexibility and adaptability of caterpillars (Fig. 1), the larvae of moths and butterflies. Their locomotion (crawling and inching) requires a soft and deformable body that does not necessarily maintain a constant volume [1].

There is an increasing need for robots capable of navigating in unstable or delicate environments (such as search and rescue applications). These environments are ideal for robots able to change their overall dimensions to fit through tight spaces [1]–[3]. The goal of this research is to design, build and control a robot that is light, soft, and deformable, resulting in a minimal impact on its operating environment. Another goal is for the robot to crawl through unstable terrain and negotiate tight spaces more easily than conventional robots.

Many current soft robots rely on off-board actuator motors or pneumatics that employ compressors to inflate chambers to actuate the body [4]–[6]. Some designs use shape memory alloy actuators (SMAs) but these require a great deal of current and are very sensitive to the environmental conditions (eg. temperature) [7]–[9]. There is a need for an onboard actuator capable of high force outputs and large length changes.

This paper describes a compressible foam motor-tendon driven soft robotic platform; with the foam properties, body design, and fabrication being the primary focus. The capabilities and performance of the platform’s initial prototype are also discussed. This actuation strategy exploits the stored energy in the expansion or recovery of a viscoelastic foam to drive the robot body forward. Using a highly deformable foam also allows for compression and bending of the body and rapid gait transitions during locomotion. The motor-tendon system simplifies motor placement by allowing the motor to act on sections of the robot in remote locations, where the end of the tendon is embedded, and not at the end of the motor output shaft. This allows for high forces to

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Fig. 1. Tobacco Hornworm (Manduca sexta) Caterpillar
Fig. 2. SquMA BOT Cross Section Schematic. Units are in millimeters and part labels are defined in Table I.

be created in preferential regions, using off-the-shelf motor solutions. The results from our prototype demonstrate the effectiveness of this method, which we believe could be beneficial for creating a distributed exploring robot platform. The design is capable of scaling to smaller and larger sizes with minimal modification to the design or control systems.

II. DESIGN AND DEVELOPMENT

The robot design is an elongated, multi-segmental, structure based on a triangular cross-section that provides stability, large ground contact, and low weight. Locomotion relies on frictional interactions with the ground, and energy is supplied by active compression and passive expansion of polyurethane foam. A motor-tendon system is used to compress the foam in preferential locations, creating a caterpillar-like gait. Tendons are embedded in the foam using bead-like anchors and then run to the motors, which are located near the center of gravity of the robot. These tendons allow the motors to actuate the foam far from their placement. The end caps are designed to be low friction in the forward direction, and higher friction in the backward direction. Similarly, the polyurethane bottom (which is high friction) is lifted off the ground to enable a forward inching motion. When at rest, this robot is unlikely to slip or roll, even on an incline. The overall design schematic is shown in Fig. 2 (above) and the body components are defined in Table I (below).

A. Body and Actuation Design

The body design is split into three subsections. These sections are designed to reflect different aspects of caterpillar motion - lifting or rearing, arching, and contracting. The red sections at the front and rear of the robot (referred to as "end caps" and labeled parts 3 and 8 in Fig. 2) are designed to compress the entire robot, turn the entire system, or lift the front end of the robot to clear obstacles. These motions are created by simply compressing one corner preferentially with tendons that run along each corner. The arching section (part 10 in Fig. 2) is designed with a preferential compression zone at its center to force the section upward. This section drives much of the inching motion and the internal triangular channel is compressed by tendons embedded at the bottom corners of the robot. The central section (section 1 in Fig. 2) is designed to give the robot a larger step by increasing the horizontal compression ability. This section has tendons embedded almost horizontally in each corner of the triangular shape to create large deformation.

The tendons used in this design, made of size 92 DuPont Kevlar® aramid thread (30 lbf break strength), are wound onto a spool within the motor casing to convert the rotational motion of the motor into a linear force on the tendon. The tension put on the tendons (approximately 18 lbf), along with the tight radius of curvature created when wrapped around the spool, limits the type of material possible for the tendons. Kevlar thread was selected for its high strength and small thread diameter. This allows for the use of conventional motors to actuate the entire robot, reducing the cost of the overall robot, as well as creating a modular motor replacement strategy. The motors used for the SquMA Bot prototype were RobotZone, LLC 44 RPM brushed DC Planetary Gear

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>BODY COMPONENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part</td>
<td>Description</td>
</tr>
<tr>
<td>1</td>
<td>Large Deformation Section</td>
</tr>
<tr>
<td>2</td>
<td>Limited Deformation Section</td>
</tr>
<tr>
<td>3</td>
<td>Lifting Motor Front Cap</td>
</tr>
<tr>
<td>4</td>
<td>Lift Motor Assembly</td>
</tr>
<tr>
<td>5</td>
<td>Compression Motor</td>
</tr>
<tr>
<td>6</td>
<td>Arching Motor</td>
</tr>
<tr>
<td>7</td>
<td>Directional Friction Roller</td>
</tr>
<tr>
<td>8</td>
<td>Turning Motor Rear Cap</td>
</tr>
<tr>
<td>9</td>
<td>Turning Motor</td>
</tr>
<tr>
<td>10</td>
<td>Arching Section</td>
</tr>
<tr>
<td>11</td>
<td>Kevlar Tendon Paths</td>
</tr>
</tbody>
</table>
motors (Model Number 638294) that generate 25 kgf-cm of torque. These motors were both small and powerful, while also offering a hall effect encoder and low operating current.

In order to quantify the range of motion for the prototype, the effect of each motor is characterized using a curvature coefficient (CC) \[ CC = \frac{x}{a} = \frac{2 \sin(\frac{\theta}{2})}{\theta} \] and the shortening coefficient is calculated using \[ SC = \frac{x}{L} \]

where \( a \) is the arc length of the actuated robot (Fig. 4), \( x \) is the cord length, \( r \) is the radius of the circle prescribed by the arc, \( \theta \) is the angle prescribed by the arc, and \( L \) is the total un-actuated length of the robot. The parameters are shown in Fig. 4 below, and the results are summarized in Table II. The turning configurations shown in Fig. 3 (e) and (f) do not actively turn the robot on their own, but instead bias the inching gait to cause a turning motion.

### TABLE II

<table>
<thead>
<tr>
<th>Motor Functions</th>
<th>CC</th>
<th>SC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rear</td>
<td>0.95</td>
<td>0.72</td>
</tr>
<tr>
<td>Right+Left</td>
<td>0.99</td>
<td>0.67</td>
</tr>
<tr>
<td>Rear+Right+Left</td>
<td>0.96</td>
<td>0.62</td>
</tr>
<tr>
<td>Lift</td>
<td>0.97</td>
<td>0.64</td>
</tr>
<tr>
<td>Right Turn</td>
<td>0.98</td>
<td>0.96</td>
</tr>
<tr>
<td>Left Turn</td>
<td>0.98</td>
<td>0.98</td>
</tr>
</tbody>
</table>

### B. Manufacturing Techniques

SQUMaBot is manufactured in several steps over the course of 2-4 days time (including 3D printing and casting the parts). Several novel techniques are used in order to combine multiple materials, and embed the motor tendon system within the foam body.

1) **Foam Molding:** The main body sections of the robot were molded in 3 parts using polyurethane foam (Smooth-On FlexFoam-IT!® III Flexible Polyurethane Foam). Molds were custom made using acrylic and parts printed in P400 ABS on a Dimension sst 1200 printer. The foam is formed in a reaction involving mixing the two materials specified by the foam manufactures. First, the mold was coated using Mann® Release Technologies Ease Release® 2831 as a releasing agent. Next, the two parts were mixed and poured into the mold. Once the foam set in the mold for 30 minutes, it was allowed to rest overnight in a incubator at 34°C. The resulting foam is a durable thermoset polyurethane.

For the deeper cavities in the High Compression section (Fig. 2. 1) and the Arching section (Fig. 2. 10), post processing of the molded foam was needed. The mold created indentations in the sections, but through holes were not possible because of curing issues. As a result, these sections required post-processing in the form of excising the through holes with a scalpel.

2) **3D printing:** The motor assemblies and housings (end-caps) were printed on the same Dimension sst 1200 printer as the mold pieces out of the same [P400 ABS] material.

3) **Assembly:** Assembly of the robot occurs in 5 parts:

   i) Kevlar tendons are inserted into the High Compression and Arching sections
   ii) Compression and arching motors are embedded into their sections and secured with silicone adhesive.
   iii) The 3 foam sections are joined using silicone adhesive
   iv) Lift and turning tendons are inserted into the body
   v) The 3D printed end-caps are added and the lift and turn tendons are secured.

To avoid the tendons pulling through the foam both within the sub-sections and along the whole body, plastic beads (12 mm) were tied onto the ends and embedded into the body with silicone adhesive. These beads both distribute the tendon force over the foam to avoid damage and reduce the stress concentration on the kevlar tendon attachment point. Due to its brittle structure, kevlar will snap if simply tied into a knot around the foam.

### C. Material Properties

The locomotion of the robot is dictated by the compression and recovery properties of the foam used. Contraction of the
body is resisted by the stiffness of the foam. Subsequent relaxation of the foam produces the locomotive force.

The stress-strain plots in Fig. 5 were obtained by compressing rectangular-prismatic foam samples to 30% of the starting thickness on an Instron machine. Ten samples were compressed for each compression rate and the data for each compression rate was then averaged. This implies that in the operational regime, the mechanical behavior of the foam is independent of strain rate.

In contrast, the unloaded recovery speed depends upon the volume of air required for restoration. In Fig. 6, we see that the free recovery velocity declines as the sample length increases. Longer samples need to take in more air to fully recover compared to shorter samples. This implies that smaller robots may move at higher relative speeds (body lengths/minute) than larger robots. While this information may not be directly applicable to the present work because the foam is recovering under a load, such a hypothesis will inform future work, especially scaling studies.

D. Control Scheme

The robot is controlled using a PC and myRio FPGA (National Instruments, Austin, TX) programmed with LabView. Gaits are not pre-programmed, but are controlled live by a user through an XBox game pad (Microsoft, Redmond, WA). When the user presses a button on the game pad, the code changes the setpoint position of the corresponding encoded motor. A bang-bang controller winds or unwinds the motor until the set point position is achieved. This control logic is presented in Fig. 7. In the LabView front panel, these set points can be adjusted on the fly to increase or decrease the compression achieved by a given motor-tendon subsystem. This control method allows customization and adaptation to a wide range of scenarios, and eliminates the need for complex sensing systems and computationally intensive learning algorithm.

III. EXPERIMENTAL RESULTS AND DISCUSSION

We characterized the performance of the robot by comparing its kinematics to that of the caterpillar, measuring its speed in relation to other soft robots, and running it through several different obstacles.

A. Biomimetic Comparison (Kinematics)

The inching gait of the robot was compared to the inching gait of a *Sphacelodes vulneraria* caterpillar. The results show a similar gait pattern (Fig. 8). The gait in the caterpillar is broken down into 6 steps:

i) Grip with the front legs.
ii) Release the back legs.
iii) Arch the body, bringing the back legs forward.
iv) Grip with the back legs.
v) Release the front legs.
vi) Relax the body, pushing the front legs forward to take a next step.

Similarly, the robot also follows a 6-step gait pattern:

i) Lay the head region flat to create a high friction area
ii) Release the back friction region
iii) Arch the body, bringing the back region forward
iv) Push with the back friction region
v) Angle the head region to release friction
vi) Relax the body, pushing the front region forward.

B. Speed Results

The robot’s speed was measured using video analysis. To ensure repeatable conditions, the robot crawled in a straight line past the camera on a wooden particle board surface. A Casio Exilim F1 Digital Camera (6 MP) at 30 frames per second was used. The speed was measured at 0.052 body lengths/sec (BL/s). We compared our robot to other soft robots by plotting their speeds in BL/s and breaking the comparison down by actuation method (Fig. 9).
C. Obstacles

The robot was tested outside a laboratory environment with a series of terrestrial obstacles. Using its adaptable kinematics, the robot was able to squeeze through a small aperture, navigate around static obstacles, push through rubble, and climb up and down inclines.

IV. CONCLUSIONS

In this paper, the design and construction of a caterpillar-inspired soft robot was presented. The robot is 85 percent soft by volume and actuated using an onboard motor tendon system. Its speed is comparable to other soft robots with off-board systems, and its foam body makes it both flexible and durable.

Caterpillar biology inspired its soft body, inching gait, and tendon driven locomotion. Caterpillars are mostly soft and have infinite degrees of freedom, yet they are able to produce a wide repertoire of repeatable motions. This robustness relies on both the morphology of the animals as well as the material properties of the body. Our robot was able to replicate the inching gait using a simple tendon-driven system without sacrificing softness or flexibility.

The majority of soft robots rely on pneumatics or other pump based system which limits their autonomy. Having a completely on-board actuation system means that we will eventually be able to eliminate its tether. This makes SquMA Bot a good candidate for long term exploration projects, as well as search and rescue missions where a tether could be caught or damaged in the terrain.

Although our current robot does not match the speed of some soft robots [GOQBot] or its caterpillar inspiration, it does show the value of a soft tendon-driven system. SquMA Bot was able to mimic the inching gait in a predictable and repeatable manner without resorting to hard joints or a limitation on degrees of freedom. The foam material allows for both infinite degrees of freedom and a robust structure resistant to damage.

In the future, we intend to replace the hard 3D 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. We would also like to explore the scalability of our design. Because SquMA Bot is not made of any hard mechanical parts, it can be easily scaled to fit a wide variety of situations. Eventually, we hope to build one large robot capable of carrying and deploying many smaller robots to a specified survey area.

ACKNOWLEDGMENT

This work was funded through NSF Grant 1144591 and NSF/IOS 1456471 to BAT, Soft Material Robotics IGERT at Tufts University, therefore we would like to acknowledge our fellow participants. Dr. Eliad Cohen, Dr. Vishesh Vikas, Ritwika Mukherjee, Niko Kastor, and Akshay Vaidya shared manufacturing techniques and technical knowledge throughout the process. We would also like to acknowledge Dr. Robert White for design feedback during the course of the project.
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