More than Skin Deep: Crawling Soft Robots with Functional Skin

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1 Introduction

Animals moving in natural environments need to adapt locomotion strategies to navigate unpredictable and constantly changing conditions. This is accomplished through alterations in descending motor commands and through compliant mechanical mechanisms such as shock absorption and tissue deformation. Traditional robots are designed to operate in static environments that favor a “top down” control system with rigid mechanical components and minimal interactions with the surroundings. However, with an increasing need for robots that can operate in human and natural environments it is important to explore strategies for incorporating compliant materials into robot design.

With these goals in mind, we have designed and built a highly compliant crawling robot based on our studies of caterpillar locomotion [1]. This robot features several innovations that make it untethered, extremely light, robust, highly deformable, and easily adapted to a variety of environments. We believe this technology could be developed to build cheap, useful, soft robots for a variety of applications including exploration in delicate environments and autonomous mobile monitoring of hazardous situations.

A major challenge facing the design of soft robots for practical applications is identifying actuators that do not impede flexibility or compressibility. There are also issues with attaching actuators to soft structures such as polymers and foam. Pneumatic inflation is one of the most common actuation methods used in soft robotics [2, 3]. Though this method generates very large displacements, gas must be delivered from a motorized compressor that is usually off-board [4]. Another common approach is to use shape memory alloys [5, 6] or electroactive polymers [7] which typically have small strains and poor energy efficiency.

To address these concerns we have designed and built a highly compliant foam bodied robot actuated by a motor-tendon system. The tendons are attached to a flexible fabric skin which prevents tearing of the foam. The skin also provides the external structure of the robot by slightly compressing the foam within. It also contains differential friction elements which allow the robot to move more effectively on many different substrates. Because the robot is electrically actuated with a relatively high power density and efficiency it can carry its own power supply and be operated entirely wirelessly.

2 Design and Development

The shape of the robot mimics the Tobacco Hornworm. We changed the tube-like shape of the caterpillar to a prism-like shape so that we could increase stability and interactions with the ground. The caterpillar relies on a passive grip, active release mechanism in its prolegs for locomotion. The robot relies on passive high friction interactions and motor activation to release and move forward.

The main structural material is a reticulated polyester foam (10 ppi) cut into a 50 cm x 10 cm prism. Small slots are cut into the foam to embed the motors, batteries, drivers, and other control hardware. A key feature of reticulated foam is that under compression the strands of polyester comprising each cell buckle and interact locally to resist further displacement. This effect helps to hold the motor housing and other components in place without the need for additional anchoring. The motors are concentrated at the rear end of the robot, and tendons are routed through the length of the body at the three corners (Fig. 1).

The entire package is encased in a stretchable fabric “skin”. The skin holds everything in place, and allows for easy attachment of the tendons at the front end of the robot. It also contains the differential friction elements. For example, the snaps and fabric sections can be embedded in silicone rubber (Ecoflex 00-10) for a high friction component, and left as smooth plastic for a low friction component. These friction components are placed at the front and rear ends of the robot to promote an inching gate.

The robot is controlled wirelessly using an on board Raspberry Pi connected via Bluetooth to an 8Bitdo SN30 2.4G gaming controller (8Bitdo Tech CO., Shenzhen, Shekou, China). The Python code registers the button events generated by the 8bitdo controller and sends motor commands accordingly. We have programmed both complicated movements such as inching directly into the controller while also leaving the ability to control individual motors. Using a python module provided by Pololu, serial commands are sent to the motor drivers to run the motors.

3 Performance

We measured the flexibility of the robot using a curvature coefficient (CC) [8], and a shortening coefficient (SC). The curvature coefficient is a dimensionless value representing the arching movement of the robot and is defined as

\[
CC = \frac{x}{a} = \frac{2\sin\left(\frac{\theta}{2}\right)}{\theta}
\]  

(1)
Friction coefficients of different materials used for SquMABot locomotion.

where $a$ is the arc length of the actuated robot, $x$ is the chord length, $r$ is the radius of the circle prescribed by the arc, and $\theta$ is the angle prescribed by the arc. Smaller values of $CC$ indicate greater curvature. The shortening coefficient represents the compression of the robot and is calculated using

$$SC = \frac{x}{L}$$

where $L$ is the total un-actuated length of the robot. With the new design, the robot is able to roll into a ball, giving it a $CC$ of 0.05 and an $SC$ of 0.5. This is a significant improvement on the max $CC$ of 0.9 and $SC$ of 0.67 in the previous design.

We also calculated friction coefficient ($F_f$) of the differential friction elements (Fig. 2). Material in contact with the substrate changes as the robot deforms, and we take advantage of this during locomotion. $F_f$ was calculated using

$$F_f = \mu \times N$$

where $F_f$ is the frictional force, $\mu$ is the coefficient of friction, and $N$ is the normal force of the robot. Though the values represent friction on a smooth substrate, these differential values are also effective at different substrates. For example, “Skin Only” has a low ($F_f$) on a smooth surface, but is much higher on something like concrete or asphalt.

4 Discussion

Like the first SquMA Bot, this Mk. II is inspired by studies of locomotion in the caterpillar and employs a soft body and tension based actuators. In addition to inching and arching over hard substrates, Mk. II also rolls over soft substrates like a flexible animal. It is able to function when tendons tangle or snap, like the way an animal would respond to unexpected stimuli or injury in nature.

For our new design, we eliminated all hard parts possible, leaving only motors and control hardware. We also eliminated the tether making SquMA Bot Mk. II completely wireless. The robot is also cheap to manufacture, making it a good candidate for exploring rough or dangerous terrain. In the future, we hope to explore the possibly of making the body of the robot out of biodegradable material, so that it has a minimal impact on the environments it explores.

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References