Rapid prototyping of insect-exoskeleton inspired robots

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1 Introduction

The arthropod exoskeleton serves both as a protective exterior, and as a mechanical transmission that routes power from muscles to wings and limbs. The exoskeleton is a multi-material continuum in which rigid and soft tissues are organized in complex three-dimensional arrangements [1]. Critically, the arrangement of these rigid and soft regions form functional mechanical systems such as linkages, springs, and even gears. Robot morphologies inspired by the insect exoskeleton may enable new multi-functional robots and further help us understand how complex arrangements of compliant elements can enable power transmission and control of biological locomotion. Insect-inspired robots have been previously developed using laminated composites [2, 3] and shape deposition manufacturing [4]. Here, we present an alternative method for rapid prototyping of robot exoskeletons that seamlessly integrates compliant and rigid materials through a custom 3D printing method using low-cost materials and standard 3D printers.

2 3D printing for multi-material robot exoskeletons

2.1 Overview

Rapid prototyping and especially 3D printing has quickly become an effective method for robot fabrication. Low-cost off the shelf 3D printers that extrude hard plastics are rapidly changing our abilities to construct robot components. In addition, soft and continuum robots [5] can be fabricated using 3D printing thanks to compliant 3D printable materials and multi-material extruding technology. However, printing multi-material systems with desired stiffness and flexibility faces limitations in: (1) limited range of material properties to choose from, (2) failure from material fatigue, and delamination at material interfaces, and (3) multi-material printers suffer from slow printing speeds and high costs of material and printers.

In this paper, we introduce a new method to 3D print flexible and resilient exoskeletons for insect inspired robots using a low-cost fused deposition material (FDM) 3D printer and standard rigid filament materials (ABS/PLA). The fundamental advance of our method relies on 3D printing rigid filaments directly onto heated thermoplastic films (Polycarbonate) which provides a flexible, yet strong backbone layer to the deposited material. Through this method we can seamlessly integrate rigid and flexible components and precisely control the stiffness properties of these systems.

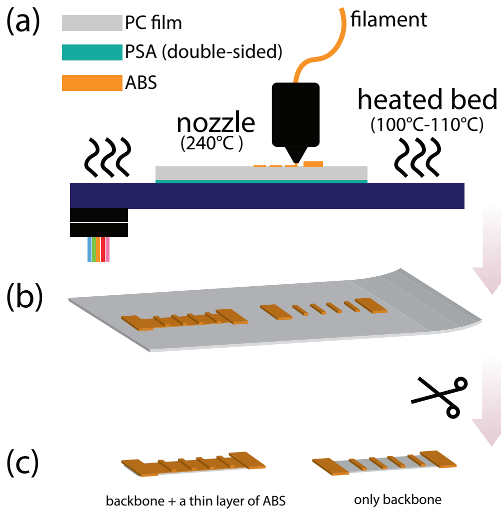

Figure 1: 3D printing process for variable stiffness exoskeletons robots. (a) A standard FDM prining process directly onto a thermoplastic base layer (b) Removing of the whole layer after cooling of the bed. (c) Excess thermoplastic is removed.

2.2 Printing method

Our method is based on a standard 3D printing process in which we print directly onto a thermoplastic base film (Figure 1). We first secure the film onto the heated bed (above 80° C) using adhesives (double-sided tape or glue stick). The printing is then started with tip of the printer nozzle in close contact with the base film which creates both high temperature and pressure concentration. The deposited material adheres well onto the heated base film under the appropriate bed temperature. We performed experiments with bed temperatures ranging from 50° C to 100° C and measured peel strength between the print material and backing material. We find that printing at a bed temperature of 100° yields the strongest peel strength for both ABS and PLA onto the PC base film.

Furthermore, we tested the performances of the proposed flexure designs from different aspects, such as flexibility, durability. The comparisons between the samples with and without the backing film proved that the film backing significantly improves durability and elastic flexibility.

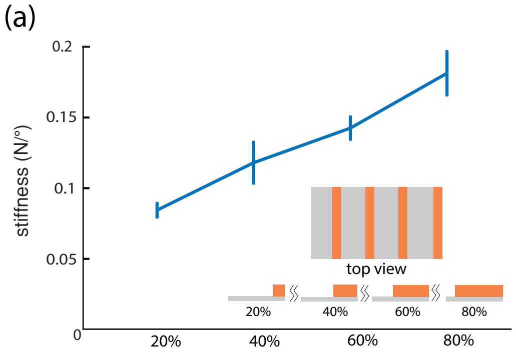

Figure 2: Stiffness measurements among different segment width factors

3 Component exploration

Programmed stiffness joints can be achieved by varying the geometries of a single segmented beam element. We vary the segment geometry by either height or width factor of the thickened material (Figure 2). Experimental results showed that the stiffness can be fine-tuned by varying the height of the segments whereas coarse-tuned by varying the width factor. Furthermore, the angles of the segments printed will further affect the bending directions of the sample beam (such as twist motion).

An asymmetric stiffness joint design is proposed by printing jammable structures on one side of the beam which significantly stiffens the joint in one direction and locks up at the extreme angle. Such a design can thus be utilized for activating multiple joints of a single flexure in a predefined sequence. However, to mimic insect leg motions from the multi-joint beam design, a simple pulling and releasing force input will not be sufficient for a hysteretic gait cycle. We thus introduced a torque reversal mechanism where the torque exerted on the jamming hinge switches sides as the tendon switches sides across the open slot (Figure 3), forcing the beam to trace a hysteretic loop cycle.

4 Multi-material legs enable complex motions

To demonstrate the capabilities of 3D printed exoskeletons, an untethered bio-inspired 2-leg crawling robot driven by a single motor is printed. This robot achieves adaptive crawling locomotion using a single servo motor. By arranging the proposed joint elements into a continuum leg design, we are able to create a hysteretic cyclic leg motion with only one motor undergoing linear motion actuated through a tendon. The multi-material legs are connected with a single motor using string. A driving signal is input from the bidirectional rotary motion which converts into a pulling and releasing actuation of either leg under an antagonistic tendon wiring configuration from the central motor disk. The 2 legs are thus driven under a cyclic motion pattern without interfering each other (Figure 3).

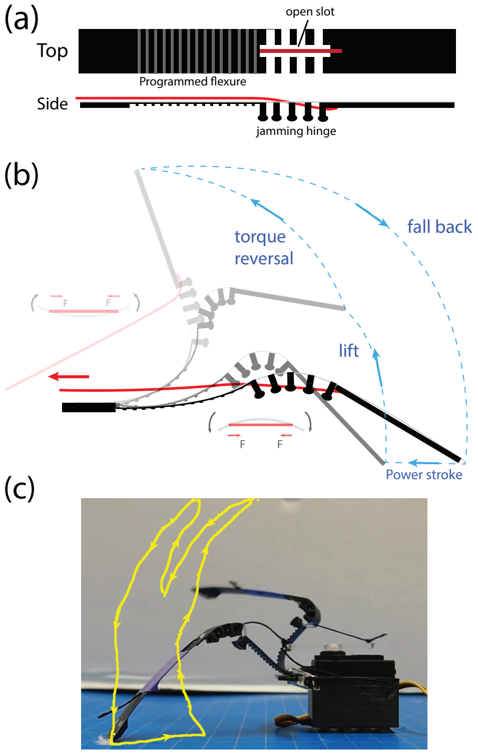

Figure 3: Design of the multi-material leg and crawling robot (a) top and side views of the leg components (b) Diagram of the leg motion (c) Tracking of one leg of the robot

5 Informing the mechanics and control of underactuated insect appendages

The work described here is inspired by the appendages of many insects in which multi-jointed and continuum structures are actuated through tendons. We hope in the future to use this rapid fabrication approach as a robotic test platform to study the control of tendon driven insect appendages. One example is that of the cockroach tarsus, which is composed of five flexibly linked segments but only actuated through a single muscle-tendon unit. Such underactuation may enable passive adaptation to surface structure. We hope to use our robot designs to study this in the future.

References

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