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A Low-cost Inchworm-inspired Soft Robot Driven by Supercoiled Polymer Artificial Muscle

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Abstract— **This paper presents a novel design of soft locomotion robot inspired by inchworm. This robot is actuated by supercoiled polymer artificial muscle (SCPAM), which are made from low-cost conductive nylon sewing threads. SCPAM generate muscle-like actuation upon heating and cooling, which can be utilized for soft locomotion robot's actuation. The proposed soft robot realizes inching locomotion by introducing friction anisotropy in its legs and contraction provided by SCPAM. Experiments are performed to evaluate the soft robot body's deformation as well as the robot's locomotion velocity when SCPAM are at different power input levels. Results exhibit that the soft robot can achieve locomotion velocity of 0.245 mm/s on the wood ground when SCPAM is powered at 0.16 W/cm. Compared to previous studies utilizing fluidic actuator, shape memory alloy (SMA) or motor & tendon for actuation of soft locomotion robot, SCPAM possesses high power-to-weight ratio, inherent compliance and low cost, making the robot more compact and more suitable for field exploration in contaminated areas. This study shows the potential of this low-cost artificial muscle to be widely used in soft locomotion robots in the future.**

I. INTRODUCTION

Natural animals have most of their bodies consisting of soft materials such as soft organs and tissues while exhibiting strong abilities to adapt in dynamically changing environments [1]. These animals from nature have offered researchers with inspiration for designing soft-material robot prototypes [2]. Soft-material robots, unlike traditional rigid-bodied robots, can exhibit good adaptability in unstructured areas, conformability to objects or terrains with various shapes and safety to interact with humans without complex control benefited from their inherent compliance [3-4].

Among the soft robot's family, soft locomotion robots are investigated by many researchers since they can extend the exploring capabilities of human by offering access to extreme, dangerous or unreachable environments [5]. Different soft robot locomotion strategies mainly include crawling [6], rolling [7], walking [8], jumping [9], swimming [10] and flying [11]. For crawling locomotion inspired by caterpillars and worms, the crawling modes can be divided into two categories: two-anchor and peristalsis [5]. These soft crawling robots have adopted various actuation methods.

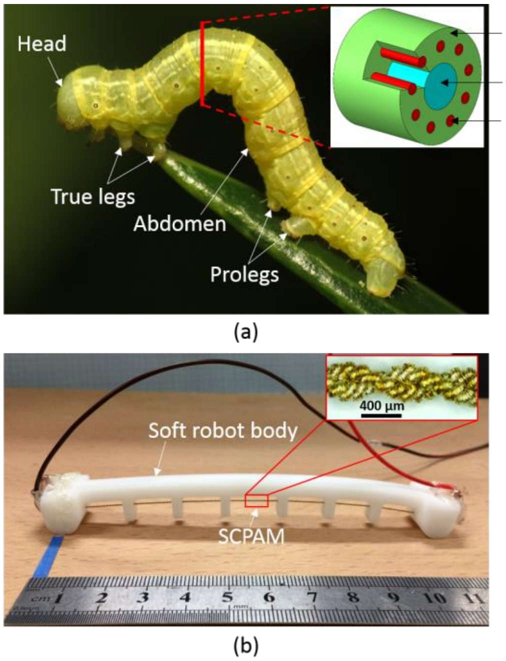

Fig. 1. Bioinspiration for proposed soft bodied robot. (a) Picture and structure of an inchworm (adapted from [32], credits to Katja Schulz, under the license CC BY 2.0, picture title 'inchworm', change is made). (b) Proposed soft robot prototype. Optical micrograph shows the microstructure of a 2-ply SCPAM.

A common method is to utilize pneumatic power for actuation. Mangan *et al.* proposed a peristaltic endoscope which was composed of three pneumatic actuators and demonstrated its locomotion in tubes [12]. Xie *et al.* designed a soft pneumatic robot with a two-anchor crawling mode inspired by inchworm [13]. In recent study conducted by Rafsanjani *et al.*, Kirigami skins are attached to a soft pneumatic actuator to realize peristaltic crawling mimicking snakes [14]. They have also developed an untethered version of the robot and demonstrated its locomotion on outdoor scenarios. Shape memory alloys (SMAs) which rely on phase transition between martensite and austenite to generate actuation, are also widely applied actuators for soft robots. Onal *et al.* adopted Origami structures as robot body and SMA as the actuator to realize earthworm-like peristaltic locomotion [15]. In the study of Umedachi *et al.,* they investigated caterpillar-inspired soft robot with a 3D-printed body and SMA actuator [16]. Aside from pneumatic actuation

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TABLE I. SUMMARY OF DIFFERENT ACTUATION APPROACHES FOR SOFT-BODIED CRAWLING ROBOT (LEGGED ROBOT EXCLUDED)

Reference	**Crawling mode**	**Inspiration**	**Actuation method**	**Is actuator soft material? (definition according to *Nature* [21])**	**Required equipment for actuation (controller not included)**
Mangan *et al* [12]	Peristalsis	Earthworm	Pneumatic	Yes	Pneumatic actuator, pump, valve, power supply
Xie *et al* [13]	Two-anchor	Caterpillar	Pneumatic	Yes	Pneumatic actuator, pump, valve, power supply
Rafsanjani *et al* [14]	Peristalsis	Snake, Kirigami	Pneumatic	Yes	Pneumatic actuator, pump, valve, power supply
Onal *et al* [15]	Peristalsis	Earthworm, Origami	SMA	No	SMA, power supply
Umedachi *et al* [16]	Two-anchor	Caterpillar	SMA	No	SMA, power supply
Vikas *et al* [17]	Two-anchor	Caterpillar	Motor & Tendon	No	Motor, tendon, transmission mechanism, power supply
Arena *et al* [18]	Peristalsis	Earthworm	IPMC	Yes	IPMC, power supply
Cao *et al* [19]	Two-anchor	Caterpillar	DEA	Yes	DEA, power supply, high voltage amplifier
Nemitz *et al* [20]	Peristalsis	Earthworm	Voice coil	No	Voice coil, power supply
Current work	Two-anchor	Caterpillar	SCPAM	Yes	SCPAM, power supply

and SMA, existing actuation means for soft crawling robots also include motor & tendon [17], ionic polymer–metal composite (IPMC) [18], dielectric elastomer actuator (DEA) [19], voice coil [20], etc.

Summary of different actuation approaches for soft crawling robot and their characteristics is listed in Table I. Pneumatic actuators can provide substantial output power and fast response. However, bulky accessories such as pumps and valves are often indispensable, making the whole robotic system less compact. SMAs can generate large stress upon thermal activation but suffers from limited controllability due to substantial hysteresis during phase transition. Motor & tendon is an efficient way for actuation and offers fast response and easy control. Whereas, affiliated transmission mechanisms and the motors often make the design complicated. Moreover, this actuation method brings in lots of rigid components which may impede the inherent compliance of soft robot. This problem also applies to SMA and voice coil actuators, which are not soft materials according to definition from the *Nature* [21]. DEAs are inherently compliant, yet the high voltage required for activation may not be unsafe for certain situations. IPMCs are also candidates for soft actuators, but their actuation force is weak.

To summarize, all of the existing actuation means for soft robot locomotion have their own merits and demerits, which creates the need for novel actuation technologies. In this study, we apply a novel actuation method for soft crawling robot, which is supercoiled polymer artificial muscle (SCPAM) constructed from low-cost nylon threads.

Recently, polymer fibers or threads have been found to be able to generate muscle-like actuation by continually twisting them to form coils [22]. Since then researchers have studied their applications in robotics such as actuators for robotic hand [23], wrist orthosis [24], reconfigurable rolling robot [25] and so on. Recently, SCPAM has also been preliminarily investigated for soft robot applications, including actuators for soft skins [26], synthetic musculoskeletal system [27] and soft grippers [28], as well as curvature sensors for shape estimation of soft robots [29]. Previous studies have not reported the application of SCPAM as actuators for soft crawling robots. Since SCPAM possesses attractive features such as high power-to-weight ratio, inherent compliance, low-cost and good customizability [30], it has high potential to be applied as actuation for soft robot locomotion.

This paper presents the application of SCPAM as actuators for a soft-bodied robot capable of inchworm-inspired locomotion (see Table I and Fig. 1). Significances of this study are concluded as follows:

1. First to apply SCPAM in a soft crawling robot;
2. Simple design of a soft robot capable of crawling locomotion;
3. Low-cost and disposable, making it suitable for exploration in hazardous environments such as contaminated fields.

In the following sections of this paper, we first introduce the soft robot design and its locomotion principle in Section II. Section III shows the fabrication of the proposed soft robot including the fabrication of SCPAM and the whole robot. In Section IV, experiments to evaluate shape deformation during actuation, as well as locomotion velocity of the soft robot, are performed and results are illustrated. Finally, conclusions are drawn, and future work is discussed in Section V.

II. ROBOT DESIGN AND LOCOMOTION PRINCIPLE

A. Biological inspiration

Robotic scientists usually get their inspirations from creatures in nature [31]. Belonging to the Geometridae family, an inchworm is a kind of caterpillar that has prolegs at the end of its body and true legs at the front (see Fig. 1(a)). The cross-section view of its abdomen is illustrated in top right of Fig. 1(a). During locomotion, the longitudinal muscle fibers contract and lead to bending of its body and shortening of its overall length. By anchoring its true legs and prolegs alternately, the inchworm realizes a looping gait. The intrinsic principle of this two-anchor crawling is anisotropic friction between the inchworm and the ground (friction coefficient in

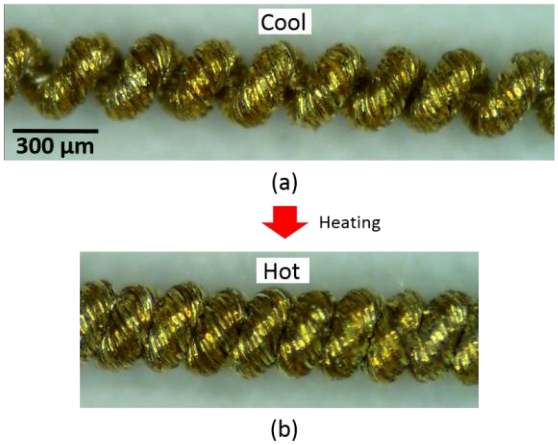

Fig. 2. Optical micrographs showing the actuation of SCPAM (1-ply). (a) Initial shape of SCPAM. (b) Shape after contraction.

the forward direction is lower than the backward direction) [5]. Inspired by this locomotion principle, we propose a soft crawling robot shown in Fig. 1(b). This soft robot utilizes SCPAM to function as longitudinal muscle and realizes lengthening and shortening. As for anisotropic friction, it is implemented by introducing variable-friction leg into the robot.

B. *Principle of locomotion*

As an artificial muscle, the actuation principle of SCPAM can be briefly explained as follows: the supercoiled polymer fiber or thread will contract in the axial direction and expand in the radial direction upon temperature rise, generating an untwisting torque and a notable contraction stroke. To demonstrate the process intuitively, micrographs showing the actuation of SCPAM is presented in Fig. 2. The optical micrographs are taken by a microscope (ZW-U500, Zhongweikechuang Inc., China). The material of SCPAM can be found in Section III-A.

The locomotion principle of proposed soft crawling robot is illustrated in Fig. 3. The soft robot consists of the robot body and the actuator—SCPAM. The muscle-like lengthening and shortening for locomotion can be realized by a pair of antagonistic actuators or an actuator for shortening and restorative force in the elastic robot body for re-lengthening. In this study, we adopt the latter method in order to simplify the robot design. As such, the elasticity of the robot body should be carefully chosen to implement the muscle-like motion.

Slippery (low friction) part is located at the edge of the soft robot body forming a variable-friction leg in order to reduce friction with the ground when the body deforms over a threshold angle [16]. The remainder of the robot body is made of silicone rubber and has higher friction with the ground compared to the slippery part. The robot is at its initial position in Fig. 3(a) and SCPAM is power off. After activation (SCPAM power on), the robot body contracts over the threshold angle and slippery part of the body is in contact with the ground pushing the body forward (see Fig. 3(b)). When SCPAM is power off again, the high friction part of the body contacts the ground and hinders the robot from moving backward (see Fig. 3(c)).). This anisotropic friction leads to forward locomotion of the robot due to the friction force that is smaller in the forward direction than in the backward direction ($F_x<F_{-x}$).

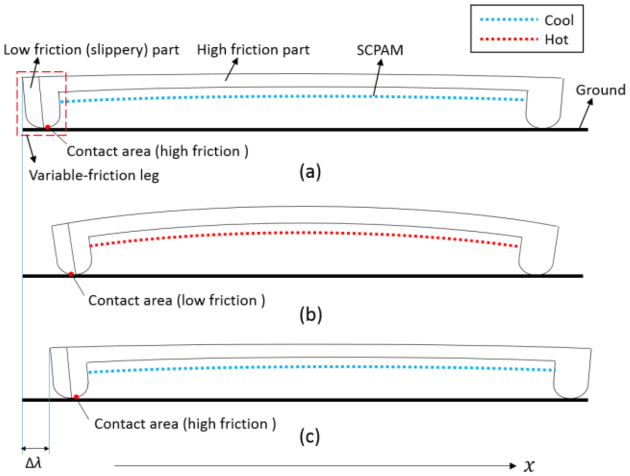

Fig. 3. Locomotion principle of the soft robot. (a) Initial position when SCPAM is power off. High friction part of the soft robot's variable-friction leg is on contact with the ground (b) Low friction part of the soft robot's variable-friction leg is on contact with the ground when SCPAM is power on and under contraction. (c) When SCPAM is power off again, the soft robot returns to its initial shape and moves forward with a distance $\Delta\lambda$ due to anisotropic friction.

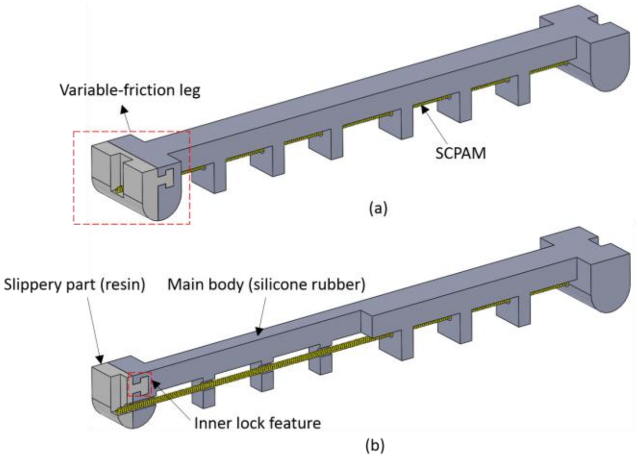

Fig. 4. The soft robot design. (a) 3D model. (b) Internal structure of the robot.

C. *Soft robot design*

Based upon the locomotion principle, a 3D model of the proposed soft robot is presented in Fig. 4. Slippery part of the robot body is inner locked to the main body for connection (see Fig. 4(b)). The main body has six guides beneath for assembly of the SCPAM, which is fixed at two ends of the robot body. In this design, most part of SCPAM is exposed in the air to facilitate its passive cooling. In the future study, we will investigate adding active cooling such as forced air to promote the response speed of the robot.

III. FABRICATION

The proposed soft robot is fabricated by integration of SCPAM into a soft robot body. This section will present the fabrication process of SCPAM firstly, and followed by the fabrication of the whole robot.

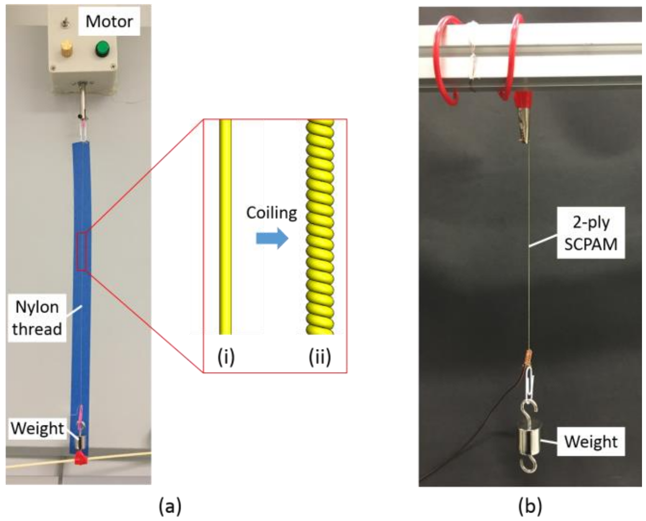

Fig. 5. Fabrication of the SCPAM. (a) Twisting and coiling of conductive nylon thread to form 1-ply SCPAM. (i) Initial thread. (ii) Coiled thread. (b) Annealing and training of 2-ply SCPAM.

A. Fabrication of SCPAM

The SCPAM applied in this study is manufactured from commercially available conductive nylon threads. These nylon threads are silver plated, and therefore the fabricated SCPAM can be electrically activated since Joule heat would be generated when electricity is passing through. Compared with monofilament nylon, artificial muscles constructed from the off-the-shelf conductive nylon thread perform slightly lower in terms of actuation strain [30]. However, they are easier to fabricate and can be sourced in large quantities.

In this study, we use Shieldex Conductive Yarns (110/34, Nylon 66, PN: 200111011034HC) to create the SCPAM. This conductive thread can be purchased at around \$0.03 per meter. The fabrication procedures are as follows:

- Continuously twist the nylon thread until it is fully coiled. The thread is fixed to a motor at one end and hanged by a weight at the other end (see Fig. 5(a)). A weight of 25 g is adopted.
- Double back the fabricated 1-ply SCPAM to form 2-ply configuration and prevent itself from unwinding.
- Anneal and train the 2-ply SCPAM to eliminate residual stress and to obtain large actuation stroke (see Fig. 5(b))). During this process, a larger hanging weight of 50 g is adopted. A voltage pulse is applied across the coiled thread (0.75V/cm, 1 s on and 9 s off) for heating and cooling.

For a 2-ply SCPAM with the length of 0.12 meter used in this study, a conductive thread of 0.6 meter will be consumed and the cost is \$0.018. Precautions and details regarding the fabrication process of SCPAM can be found in [22], [30] and [33].

B. Fabrication of the soft robot

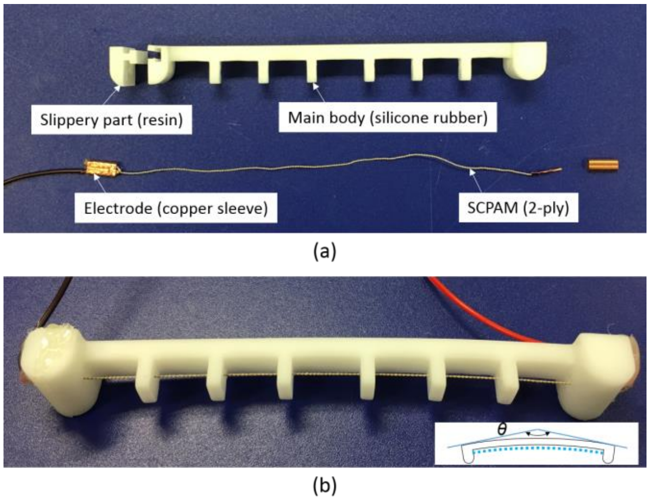

Fig. 6. Fabrication of the soft robot. (a) Components of the robot. (b) Prototype after assembly.

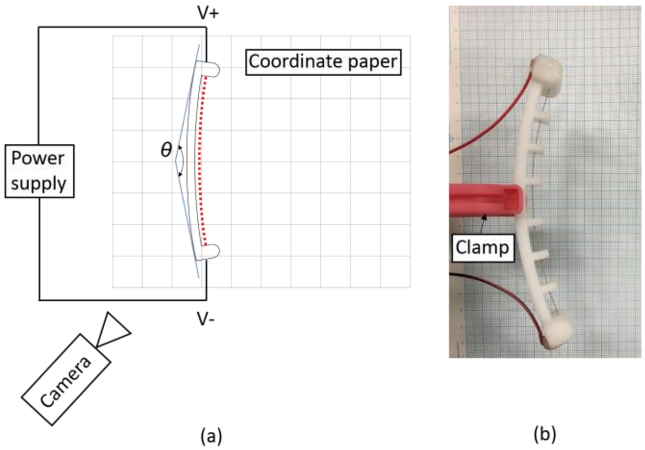

Fig. 7. Deformation test. (a) Test setup diagram. (b) Snapshot during the test.

As explained in locomotion principle, the soft robot body has two parts: slippery part of low friction in contact with the ground and main body of high friction. These two parts are made of two kinds of materials. The slippery part is made of resin (DSM Somos Stereolithography Resins-8000 Series) with stereolithography (SLA) 3D printer. The main body is molded from silicone rubber with Shore Hardness 70A. The elasticity of the silicone rubber should be adequate so that the main body can provide sufficient restorative force for re-lengthening meanwhile compliant enough to be deformed during shortening. In this study, the fabrication of the soft body's two parts is separated by WeNext Technology Co., Ltd. China and the cost is \$19.9. The total cost of the robot is about \$19.92, which can be further reduced with mass production and improved fabrication. This low-cost soft robot can be suitable for certain applications such as single use in contaminated environment explorations.

To accelerate the fabrication process, the soft robot body could also be directly 3D printed without the need for assembly using a multi-material 3D printer. Components of the soft robot are shown in Fig. 6(a) and the robot prototype after assembly can be seen in Fig. 6(b). SCPAM is assembled to the robot body with a pre-stress of 0.2 N, and the robot body is bent with an angle of θ=175° (θ is indicated in Fig. 6(b)). Hot melt glue is utilized to fix the electrodes of SCPAM to the robot.

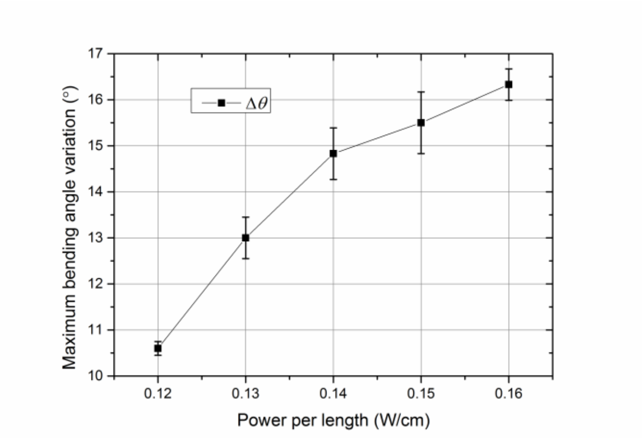

Fig. 8. Deformation test result showing the relationship between power input of SCPAM (measured by power per length) and maximum bending angle variation $\Delta\theta$.

IV. EXPERIMENTS

In this section, experiments are conducted to evaluate the soft robot's shape deformation during actuation firstly. Then locomotion on different materials is demonstrated, and the locomotion velocity is quantified.

A. Soft robot deformation test

Prior to locomotion tests, the soft robot body's deformation at different input power levels of SCPAM is examined firstly. The diagram of the robot body deformation test set-up is presented in Fig. 7. The soft robot is placed horizontally to avoid the influence of gravity. Its middle body part is clamped while a camera and coordinate paper record the bending angle variation $\Delta\theta$. Input power for SCPAM is provided by a DC power supply (NSP-2050, Manson Engineering Industrial Ltd.). In this study, power per length is applied as the power input for SCPAM.

During the test, power input varies from 0.12 W/cm to 0.16 W/cm with an interval of 0.01 W/cm. At each power level, the power is 5 s on for heating and 5 s off for cooling, forming a cycle. The maximum bending angle variation is measured during this process. The cycles are repeated three times and average values together with standard deviations are calculated. As shown in Fig. 8, the test results indicate the robot achieves larger bending angle variation at larger power input. However, the power input cannot be too large since the excessive heat would burn and damage the nylon thread.

B. Locomotion demonstration

In this paper, we perform locomotion demonstration of the soft robot on two kinds of materials: PP (polypropylene) and wood. The locomotion snapshots are shown in Fig. 9. Power input for this demo is 0.15 W/cm, and actuation cycle is also 5 s on for heating and 5 s off for cooling. It can be seen that the soft robot moves forward with a distance at the end of each heating process. The robot also moves faster on a wood plate than PP plate under the same power input conditions.

A video showing the soft robot's locomotion is uploaded as a supplementary file with this paper.

Fig. 9. Locomotion demonstration of proposed soft robot. (a) Locomotion on PP board. (b) Locomotion on wood board.

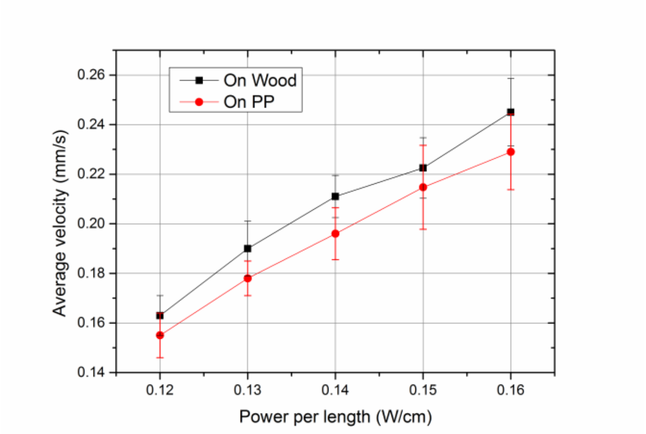

Fig. 10. Locomotion velocity test result.

C. Locomotion velocity test

Following the locomotion demonstration, velocity test is performed to quantify the soft robot's inching speed at different input power levels and on different ground materials (PP and wood). The actuation cycle is same as locomotion demonstration and power input for SCPAM varies from 0.12 W/cm to 0.16 W/cm with 0.01 W/cm's interval just like the deformation test. A ruler and camera record the forward distance change at different times. 10 actuation cycles are performed at each power level, and average velocity is calculated. The velocity test result is given in Fig. 10.

From the test result, the soft robot exhibits a larger velocity at larger power input, which has consistent variation tendency with the deformation test result in Section IV-A. Larger power input leads to larger bending angle variation, which may contribute to a larger forward distance $\Delta\lambda$ (see Fig. 3) at each actuation cycle or gait. Besides, the test result also indicates the soft robot moves faster on wood than on PP at different power input levels. When SCPAM is powered at 0.16 W/cm, the robot achieves locomotion velocity of 0.245 mm/s on wood, larger than 0.229 mm/s on PP. This could be explained that friction anisotropy between the robot body and the ground is more evident on wood than on PP. In the future study, we will investigate the robot's locomotion on more ground materials and even outdoor scenarios. The robot's locomotion velocity can also be increased by introducing active cooling and improved power input strategy such as a short pulse.

V. CONCLUSION AND FUTURE WORK

In this work, we report a low-cost inchworm-inspired soft robot design. Unlike previous studies that mostly utilize fluidic actuators, motor & tendon or SMA for soft crawling robot's actuation, the proposed robot is actuated by a low-cost artificial muscle—SCPAM. Biological inspiration, locomotion principle and fabrication of proposed soft crawling robot are presented. Experiment results have shown the effectiveness of locomotion principle and quantify the locomotion speed on two different ground materials. This paper is the first attempt to apply SCPAM as the actuator for soft crawling robot. It is expected that our study would inspire more researchers to apply SCPAM in soft robots due to its superior properties.

Future works include establishing a theoretical model of this soft robot, adding thermal sensors to realize feedback control, improving power input strategy to increase velocity speed, adding steering capability and attempt for untethered soft crawling robot design.

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