An inchworm-inspired robot based on modular body and electronics and passive friction pads performing the two-anchor crawl gait

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Abstract

We have created an inchworm capable of the two-anchor crawl gait on level ground and inclined plane. The main novelty is in the design of the inchworm: (1) three-part body that is 3D printed and actuated by two servo motors to allow a looping and lengthening action, (2) passive friction pads to anchor the feet, each of which may be disengaged using a servo motor actuated lever arm, and (3) modular body and electronics. The robot is about 2 feet in length, has a mass of about 4 kg, and uses an open-loop controller to achieve steady crawling gait. The inchworm robot achieved a speed of 1 in/s on level ground as well as on an incline of 19°. The energy usage as measured by the Mechanical Cost of Transport (a non-dimensional number defined as the energy used per unit weight per unit distance moved) is 3.38. Our results indicate that simple robotic designs that copy the basic features of natural organisms provide a promising alternative over conventional wheeled robots.

Keywords: Inchworm, Bioinspiration, Two-anchor crawl gait, 3D printing, sliding locomotion, Cost Of Transport.

1 Introduction

There is an increasing trend to emulate the form and function of biological organisms to create new robot design and/or new control approaches. Such robots may be better suited at adapting to natural environments (e.g., rough terrain) as well as man-made environments (e.g., cluttered warehouse), potentially leading to new applications. Another benefit of bio-inspiration and/or biomimicry is to understand natural organisms by recreating them. The fundamental issues in reverse engineering organisms are the lack of availability of engineering materials and actuators similar to nature and lack of a detailed understanding of how animals control their movements. Thus, a challenge is to arrive at a creative solution using existing materials and methods. This paper focusses on the design and control aspects of recreating the motion of an inchworm.

The word “inchworm” is perhaps a misnomer because an inchworm is not a worm but a caterpillar. Worms do not have legs and move around by exerting forces on the ground by undulating their body. Caterpillars, on the other hand, have legs all along their bodies and use them to move in a crawling gait. The inchworm has legs in the front and back but none at their mid-section. They use a peculiar looping motion also known as the two-anchor crawling gait for locomotion. The characteristics of the gait are anchoring of the front legs followed by pulling to make the body loop around followed by anchoring of rear legs followed by pushing to complete one gait cycle.

Past work on robot inchworm may be distinguished from each other based on the overall design (continuous versus modular body), the fabrication method (e.g., 3D printing, machining), the nature of the material (soft, hard, and a combination), type of actuation (shape memory alloy or SMA, electric motors), and type of adhesion mechanism for anchoring (active versus passive). We first review past approaches followed by an overview of our design and novelty.

Koh and Cho [1, 2] used laser micro-machining to cut smart composite microstructure (SCM). SCM forms the rigid elements that are connected by flexible joints made from copper-laminated (polyimide) films. The inchworm is actuated by a shape memory alloy wires embedded along its length and width, enabling the robot is able to crawl and turn. Wang et al. [3] created an inchworm using smart soft composites consisting of SMA wires, polydimethylsiloxane (PDMS, a silicone), and a thin polyvinyl chloride (PVC) plate. There were two SMA wires that run through the length of the robot. By sequentially actuating the two wires, the robot is able to bend longitudinally to produce forward motion. Also, two more wires run along the width and their sequential actuation allows the robot to turn. Kim et al. [4] used a similar approach wherein nickel-titanium SMA wires were pre-strained and embedded in a glass fiber reinforced polymer. The inchworm achieved forward locomotion based on a simple on-off type control of the electric current to the SMA wire. Felton et al. [5] created a two-link robot attached by a hinge joint and actuated by a servo motor to achieve the looping behavior. The individual robot parts were made from four layers: 1 layer of Polyetheretherketone (PEEK) as a substrate followed by a layer of copper-polyimide with SMA wires to activate folding behavior and 2 layers of Prestretched polystyrene (PSPS) as the contractile element. Umedachi et al. [6] created a highly deformable inchworm by 3D printing two materials on top of each other: a soft rubber-like material and a hard material. The use of the two materials with different friction properties is essential to realize the anchor and pull and anchor and push mechanism of the inchworm. Two SMA wires embedded along the length of the robot allows the robot to change is shape from flat to a loop to create forward motion. Ning et al. [7] created a minimalistic pneumatic soft robot. The robot is made up of silicone rubber using soft lithography technique and has a saw-tooth profile with air channels. Normally, the robot is flat against the ground but forms a concave shape when the air channels are pressurized. The surface is tailored to have different friction coefficients for front and back ends as well as before and after being pressurized to execute forward motion.

Kotay and Rus [8] created an inchworm that has four serial links and three electromagnetic actuators at each joint for moving forward. In addition, a fourth actuator at on one of the end links allowed for turning motion. Each of the end-link has an electromagnet that may be attached and detached as needed The robot was able to traverse vertically, horizontally, and in an inverted position on ferric surfaces using the electromagnets. Wang et al. [9] had a similar design with the only difference in the adhesion module. The adhesion module consisted of a suction cup on each end link that passively attached to the surface. A solenoid-driven release mechanism was used to detach the suction cup.

Lee et al. [10] created a minimalistic design consisting of the single piece body and two claws. The rear claw was fixed but the front claw was attached to an electro-magnetic oscillator actuator. The input to the actuator was a square wave consisting of an amplitude and frequency. By proper tuning of the two inputs, the robot was able to achieve forward movement. Lobontiu et al. [11] created a similar-type of micro-scale robot. The body was made up of a piezoelectric actuator that served as the actuation module as well as the structural element. Two rigid links were attached to the piezo through pin joints and served as legs. By exciting the piezoelectric actuator at different frequency forward locomotion was achieved.

In this paper, we present the design of the inchworm as a set of modular pieces actuated by modular electronics (Dynamixel and OpenCM by Robotis, Inc). Our design consists of three links: two end-sections for the feet and one mid-section for the body. An actuator between each foot and body allows for relative motion between the two sections to create the looping gait. Friction pads on the feet allow for adhesion. Each foot has a lever arm that helps change the friction properties by changing the surface contact area. The novelty of our design is the mechanism for anchoring and disengagement of the feet and the use of modular body and electronics. The efficacy of the approach is demonstrated by two-anchor crawl gait experiments on level ground and on an inclined plane.

2 Materials and Methods

2.1 Bio-inspiration

Inchworm morphology: An inchworm is a type of caterpillar that belongs to the family of geometrid moth. As depicted in Fig. 1, the inchworm consists of three major parts: head, thorax, and abdomen. Unlike most caterpillars, the inchworm does not have legs throughout its body. It has a set of legs in the front called the true legs and flesh structure that resembles legs on the rear called prolegs. The legs provide the necessary friction that allows the inchworm to anchor to the surface and generate movement.

Movement of the inchworm: The lack of legs in the mid-section is perhaps the main reason why the inchworm uses a unique crawling gait not seen in a traditional caterpillar. The gait has a characteristic looping motion and is called the two-anchor crawling gait, as shown in Fig. 1. The gait starts with anchoring of the true leg against the ground and the prolegs are detached. Then the muscles on the abdomen are used to pull the body in the characteristic loop shape. Then the prolegs are anchored while the true legs are detached. The muscles in the body then straighten the body thus completing a gait cycle. In the course of the complete gait cycle, the inchworm has moved a stride length as shown.

Bioinspiration: To reproduce the two-anchor crawl of the inchworm, we need the following two features: (1) the ability to create a loop, and (2) the ability to anchor to the ground to pull and push as needed. The next section details the design of our inchworm robot.

2.2 Overview of the mechanical design

Figure 2 (a) shows an exploded view and (b) shows the final design of the inchworm. The body of the inchworm consists of a mid-section and two identical end-sections. Each end-section has an actuated lever arm. Adhesive pads are placed on the surface of the end-sections that contacts the ground. The overall length of the robot is 26″, width 7.5″, height 2.75″, and overall weight is 3.93 kg.

Inchworm body: The mid-section and the two end-body section are of dimension 5” $\times$ 5” $\times$ 3”. This is the minimum size needed to accommodate the actuators and the electronics module. A connecting link attaches each end-section to the mid-section. The connecting link has a pin joint on either side. The pin joint to the mid-section is un-actuated while the pin joint to the end section has an actuator to enable lifting of the mid-section. The micro-controller, the expansion board, and the Bluetooth module are all placed in the mid-section. The end-sections, mid-section, and the connecting links are 3D printed using the Ultimaker 3 Extended using Polylactic Acid (PLA) filament. The system is tethered, it is powered by an external power supply. The modular design of the body, two end-sections, and mid-section allow the robot to achieve the looping gait by rotating the connecting link using the actuators.

Anchoring using friction pads: Friction pads were used to achieve a simple passive anchoring. The friction pads are from egrips (Alta Partners LLC, Westlake, OH) and consist of a silicone material. These pads are generally used to cover cell phone surfaces to provide adequate friction while gripping. The friction pads are attached to the end-sections as shown in Fig. 3 (a). To determine the friction coefficient, we placed one of the end-section on an adjustable ramp. The slope of the ramp was gradually increased till the end-section begin to slip under its own load. By determining the tangent of the angle made by the ramp with the horizontal surface, the coefficient of of friction was determined to be 1.3.

Lever arm with roller wheels for reducing friction: The friction pads have sufficient friction to allow anchoring of the end-sections. However, in order to move efficiently, we need to reduce the friction. This is achieved by using a lever arm with a roller ball (KangTeer, China) on each end-section as shown in Fig. 2. Each lever arm is controlled by an independent actuator. During anchoring of a particular end-section, the lever arm is set at an angle such that the roller bearing does not make contact with the ground as shown in Fig. 3 (b). To release the friction pad, the actuator moves the lever arm such that the roller makes contact with the ground and the friction pad is disengaged as shown in Fig. 3 (c). The end-section can now smoothly roll as the actuator rotates the connecting link to be parallel to the ground.

2.3 Actuator selection

There are four identical actuators in our setup. Each end-section has two actuators enclosed in a box-type setup. One of the actuators rotates the connecting link to move the mid-section relative to the end-section to move the robot forward by alternating between the looping and straightening. The other actuator rotates the lever arm with the roller to change the friction properties between end-section and the ground.

The actuator on the connecting link needs to have sufficient torque to lift the mid-section. Fig. 4 shows the Free Body Diagram of the mid-section. Let the weight of the mid-section be W. Since there are two actuators that lift the mid-section, the effective load on each actuator is $0.5W$. If the length of the connecting link is ℓ and half the length of the mid-section is L then the torque needed is $\tau = 0.5W(L + \ell\cos\theta)$, where θ is the angle between the connecting link and the horizontal. The maximum torque is needed when the robot is in the straight configuration, that is, $\theta = 0$. Thus, $\tau_{\text{max}} = 0.5W(L + \ell)$. In our case, $W = 1.33$ N and $L = 0.064$ m and $\ell = 0.076$ m. Thus, the maximum torque $\tau_{\text{max}} = 0.09$ Nm. We choose the Dynamixel motors AX-18A which has a stall torque of $\tau_{\text{stall}} = 1.8$ Nm, which is about a factor 20 over the stall torque of the motor. The AX-18A has a no load speed of 97 rpm or $\omega_{\text{no-load}} = 10.15$ rad/s. The torque-speed relation for a DC motor is

$$\omega = -\frac{\omega_{\text{no-load}}}{\tau_{\text{stall}}}\tau + \omega_{\text{no-load}} \tag{1}$$

Putting the $\tau = \tau_{\text{max}}$, we compute $\omega = 9.64$ rad/s. This is the maximum speed of the motor for the maximum load encountered.

2.4 Electronics

Figure 5 shows a block diagram of the electronics. All electronics components are from Robotis Inc. (LakeForest, CA). The microcontroller is an Open CM 9.04 and is based on

32bit ARM Cortex-M3. The microcontroller is programmed using an Arduino-like IDE called Open CM using C. The Open CM 9.04 is connected to an OpenCM 485 Expansion Board. The expansion board is required in order to operate the high voltage and current devices such as the Dynamixel motors. All the communication is serial and is based on Transistor-Transistor Logic (TTL). The expansion board connects to the AX-18A Dynamixel motors in each end-section. Dynamixels allows daisy chaining: each AX-18A actuating the lever arm is connected to the AX-18A that actuates the connecting link, the latter is then connected to the expansion board. The Dynamixel motors include a direct current motor with reduction gearhead, encoders, controller, driver, and network, all as a single unit. The motors can be used in position control or speed control mode, but they are exclusively used in the position control mode in our application. A Bluetooth module BT-210 (Robotis, Inc.) is connected to the Open CM 9.04 and is used for teleoperating the inchworm via a smartphone Robotis app.

3 Results and Discussion

We used an open loop, time-based, control algorithm to create the two-anchor crawl gait. The Fig. 6 shows a single stride for the robotic inchworm. In (a), the robot starts off with the rear arm engaged which reduces the friction coefficient between the rear body and the ground. The front part of the body is anchored due to the friction pad. Next in (b), both the motors on the connecting link are commanded to rotate by a specific amount in a specified amount of time to create the loop. Due to front anchor, only the rear part of the body moves forward. Next in (c), the front arm is engaged while the rear arm is disengaged. This causes the friction coefficient on the front body to decrease while the rear body is anchored. Next in (d), both the motors on the connecting link are commanded to rotate to straighten the body. Finally in (e), the rear arm is engaged and the front arm is disengaged anchoring the front arm to repeat the same cycle. As seen from the figure, the robot has moved forward by a fixed distance after one cycle, one stride length. A video of the robot in action is in reference [12].

The motion of the inchworm is purely kinematic. Assuming no slipping, we can compute the distance traveled in one stride as follows. The connecting link length is $3'' = 7.62$ cm. We set the turning angle to 26° (angle between connecting link and horizontal). Thus the effective distance moved in a gait cycle is $2 \times 3(1 - \cos 60^\circ) = 3''$. The time for one stride is 2.87 sec and was computed from the video of the motion. Thus the average speed as measured by the distance traveled in on stride to the time taken is 1.04 inch/sec.

The robot can climb a maximum inclination of 19°. The inclination is not limited by the actuators torques but by the coefficient of friction between rollers and the surface. Beyond the maximum inclination, the friction pad loses traction and the robot moves downward. Fig. 7 shows the inchworm robot climbing an 19° incline carrying a weight of 0.45 kg at a speed of 1 inch/sec.

The Mechanical Cost Of Transport (MCOT) for two-anchor crawl is given by [13]

$$\begin{aligned} MCOT &= \frac{\text{Energy used}}{\text{Weight} \times \text{Distance Travelled}} \\ &= \mu_{\text{forward}} g \end{aligned} \tag{2}$$

where μ_{forward} is the friction coefficient during the pull or push phase and g is gravity. In our case the friction coefficient during forward motion is 0.34, thus the MCOT $= 0.34 \times 9.81 = 3.38$. The MCOT for walking human is 0.05, for flying birds is 0.4, and for a cyclist is 0.01 [14]. Thus we observe that sliding locomotion is at least an order of magnitude more expensive than wheeled, legged, and flying modes of movement. The energetic inefficiency of sliding locomotion is a major drawback of the inchworm gait.

The anchoring mechanism is clearly the most important feature that allows forward motion without slip. In our case, the slipping was minimal for flat ground but increased as the slope increased. Because the friction was limited to 0.34, the robot could only climb a slope of 19°. By incorporating better friction material, the inchworm robot could potentially climb steeper slopes. Other designs have considered using powered suction devices for anchoring (e.g., electro-conjugate fluids [15]), which complicates the design. Another technique is to use magnetic materials (e.g., electromagnets [8]) but this limits the motion to ferric and magnetic surfaces only.

We have used a modular design. Each foot has a friction pad, a motor actuated connecting link, and a motor actuated lever arm to detach the friction pad. Furthermore, the motors are modular as each have their own controller, motor driver, and network, and allows for daisy chaining multiple motors to easily create serial link-type robot. The advantage of such modular design is that it can be easily extended to create more complex robots. For example, a caterpillar can be created by concatenating multiple feet together. We needed two motors to create the pulling and pushing motion and two more for anchoring and disengaging. This makes the design fairly complex and expensive. Although previous work by other researchers have used minimalistic designs (e.g., a single actuator and single degree of freedom robot [7]), such design have lower controllability. Electromagnetic actuators have greater power to weight ratio than shape memory alloys, the most dominant technique for actuation of robotic inchworms, for application with robot weights greater than 100 gm [16]. Thus, it is recommended to use SMA's for micro-scale robots but resort to an electromagnetic actuator for macro-scale robots.

Our inchworm robot is limited in a few aspects. The robot is power tethered thus limiting the robot to short distances. A true autonomous robot with batteries on board is promising for navigation in pipes and unstructured terrain. The robotic inchworm has only demonstrated the two-anchor gait, but a living inchworm is capable of more gaits such as climbing, standing, and steering [2]. Though it should not be too hard to add steering motion, standing is limited by the torque capacity of the robot and climbing walls is limited by the anchoring capacity of the robot. A design that has higher adhesion, higher torque capacity yet lightweight will provide a more versatile library of motions.

4 Conclusion

We have demonstrated two-anchor crawling motion inspired by inchworm locomotion. The main novelty is the use of a modular robot and electronics and anchoring mechanism using passive friction pads and disengagement using actuated lever arms. Such simple mobile robots inspired from biology may be able to navigate on uneven and unstructured surfaces and holds a promising application in search and rescue missions.

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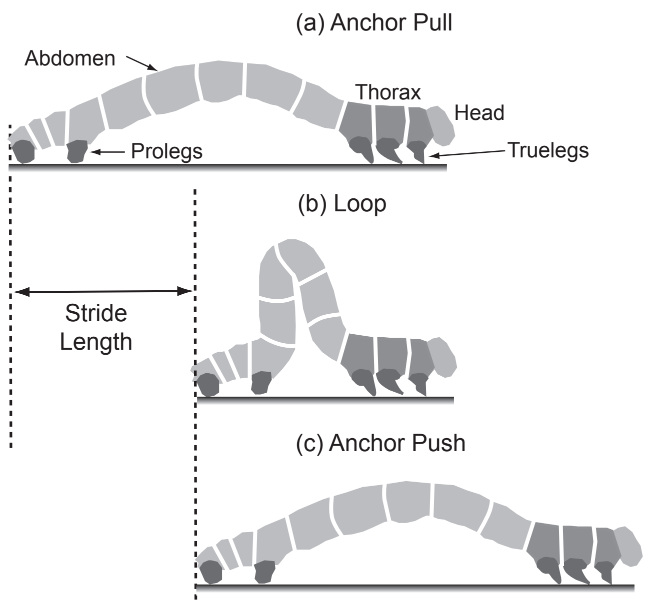

Figure 1: Two-anchor crawl gait of the inchworm. The figure has been redrawn from [3].

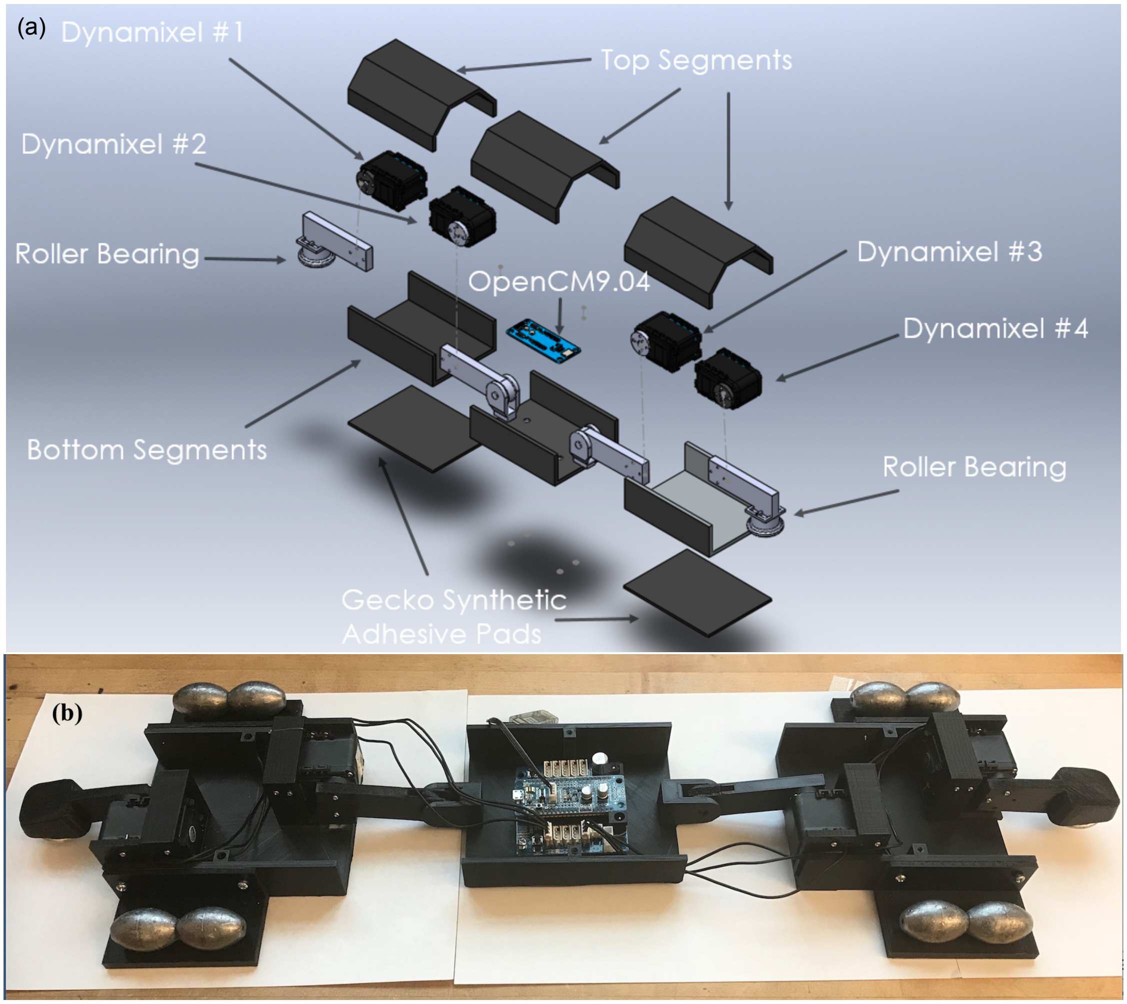

Figure 2: Inchworm (a) exploded view (b) final built

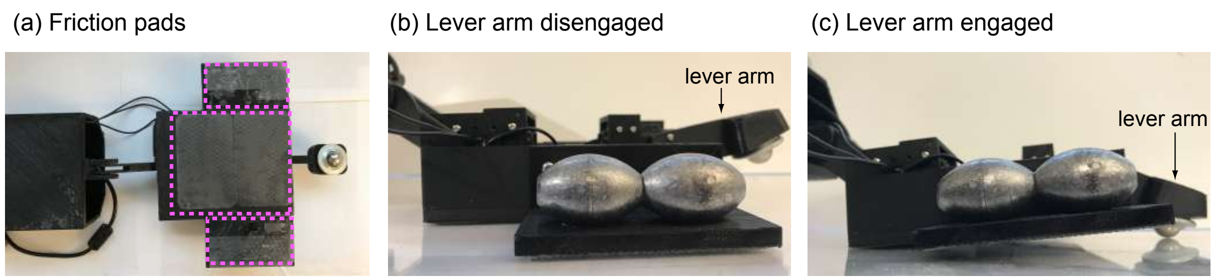

Figure 3: Anchoring mechanism: (a) Friction pads are attached to the end sections of the body, (b) when lever arm is up, the friction pads contacts the ground and the corresponding section is anchored, (c) when lever arm is moved down, the section makes line contact with the ground and the corresponding section is not anchored, thus the section can slide easily.

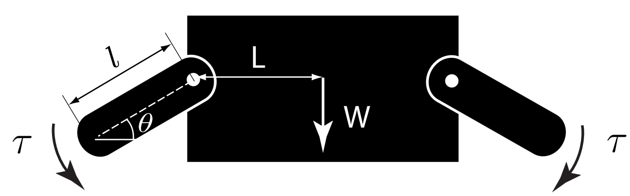

Figure 4: Free body diagram of the middle block used for actuator torque calculation.

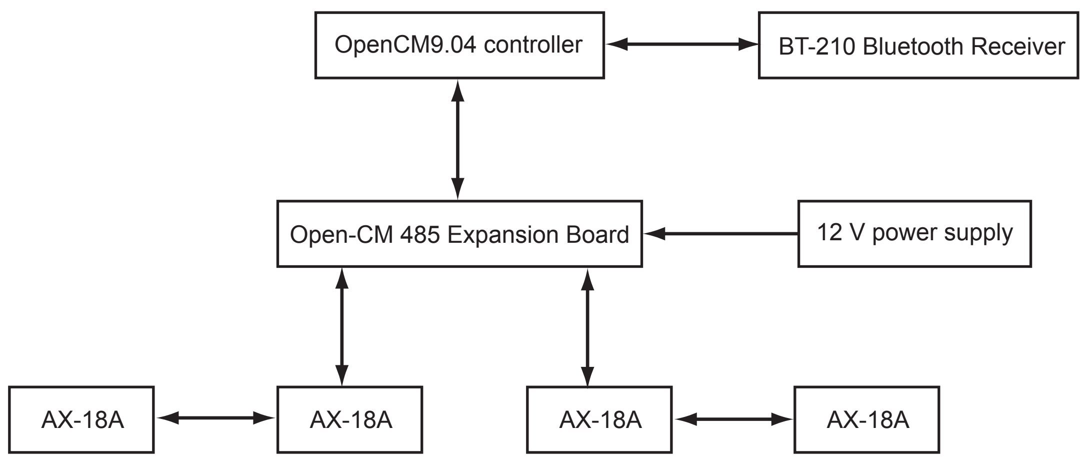

Figure 5: Block diagram of the electronics and actuators.

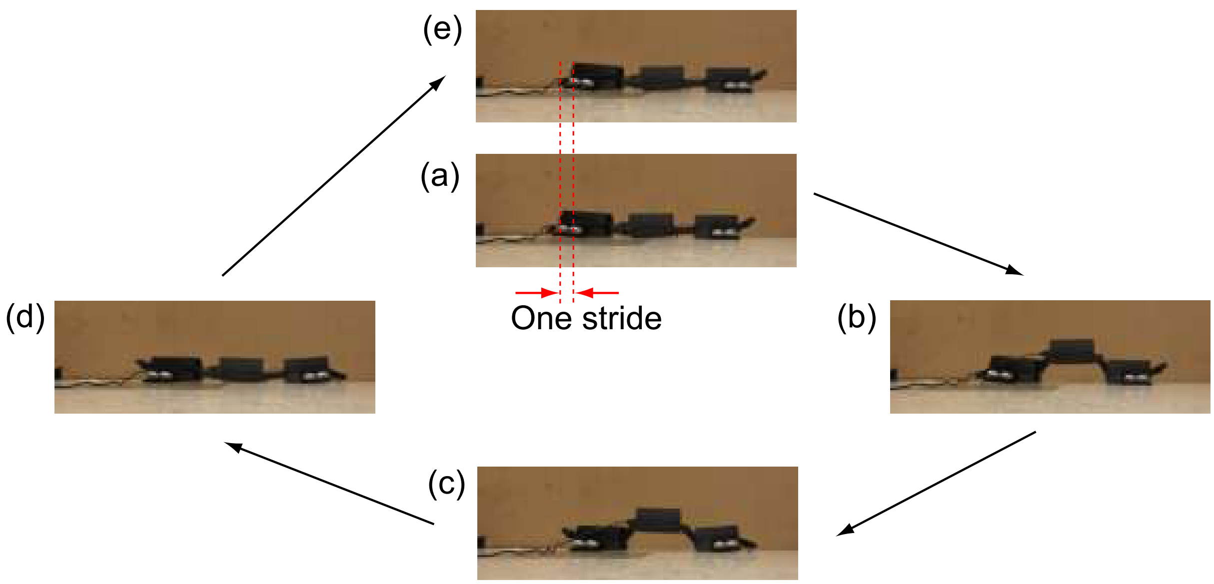

Figure 6: Two anchor crawl gait: (a) Rear arm engaged, front is anchored. (b) Front anchor pull, (c) Front arm engaged, rear is anchored, (d) Rear anchor push, (e) Rear arm engaged, front is anchored (same as a). This completes one stride for the inchworm robot.

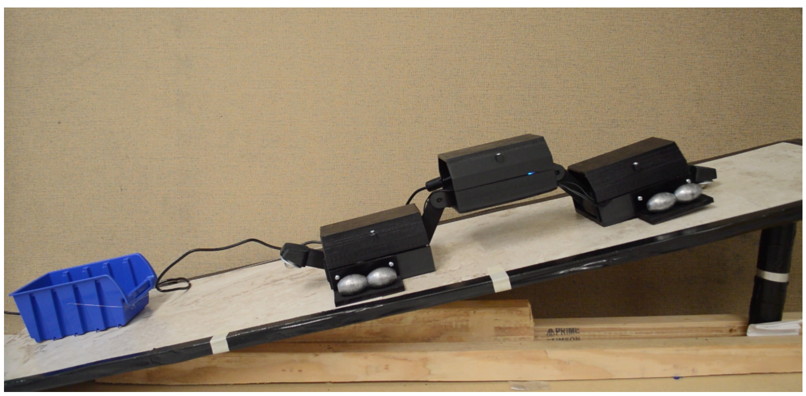

Figure 7: The 3.93 kg robot is hauling a weight of 0.45 kg at a speed of 1 inch/sec on a 18° incline.

List of Figures