UNIVERSITY OF ILLINOIS AT URBANA - CHAMPAIGN

Earthworm Robot

Design Document

Project #56

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I. Introduction

A. Objectives

The purpose of this project is to construct a robot designed to emulate the earthworms' shape and muscle with artificial material, and their movement patterns with electrically powered actuations and computer controlled locomotion.

B. Background

Mechanisms enabling limbless movement has the special attribute of being versatile with relatively simple and repetitive structures. Biomimicry is the engineering emulation of time-tested and nature-inspired solution to problems in the nature environment, and examples of limbless mechanisms includes bacterias, snakes, worms, etc. While the emulation of snake's moving patterns have seen implementations, we are inspired by earthworm's ability to crawl through surfaces of different drift, density, and composition (i.e. dirt, sand, and obstacles fields), due credit to its elastic body structure, circular and longitudinal muscles, and the movement patterns controlled by them [7].

The robot can be extended to equip with modules for specific tasks [4]. For example, in the area of agriculture and environmental studies, the robot can be equipped with an array of sensors and sample collector to conduct geological surveys with minimal disturbance. Another potential application is search and rescue, where the robot can crawl through obstacles, locate target, and potentially relay materials and serve as a communication link .

C. High-Level Requirement list

1. Robot must be capable of longitudinal and circular actuation
2. Robot must e capable of mimicking the 3D locomotion exhibited by earth worm

II. Design

A. Block Diagram

This project divides up into four modules: control, power, actuation, and sensor. Details of each can be found in the following sections.

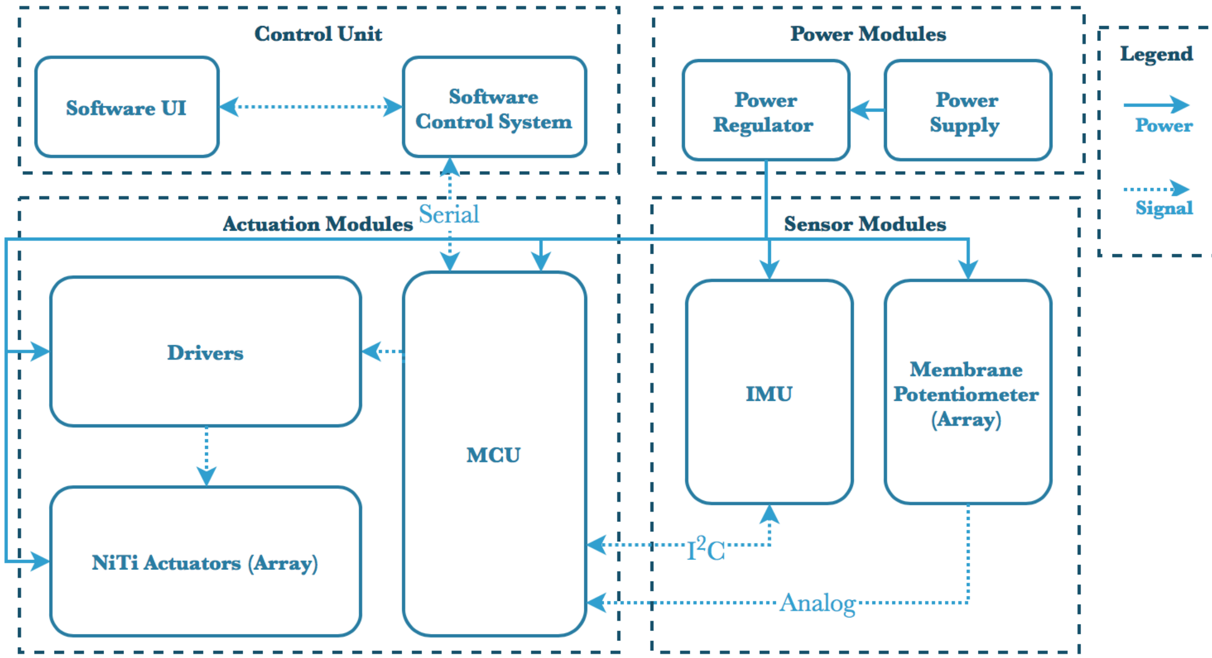

Fig.1 Block diagram of the robot and its control

B. Physical Design

The body of the robot is made with a mesh with length 60mm and radius 10mm in the uncompressed state. It is wrapped with 5 evenly spaced custom-made nitinol actuators for circular actuation. These are supported by 4 evenly spaced tendons composed of wires and nitinol actuators for longitudinal actuation. The power and control circuit is connected to the robot via the wires (with gap lager than depicted). The IMU is placed near one end of the worm and the pressure sensor is placed along the worm's body.

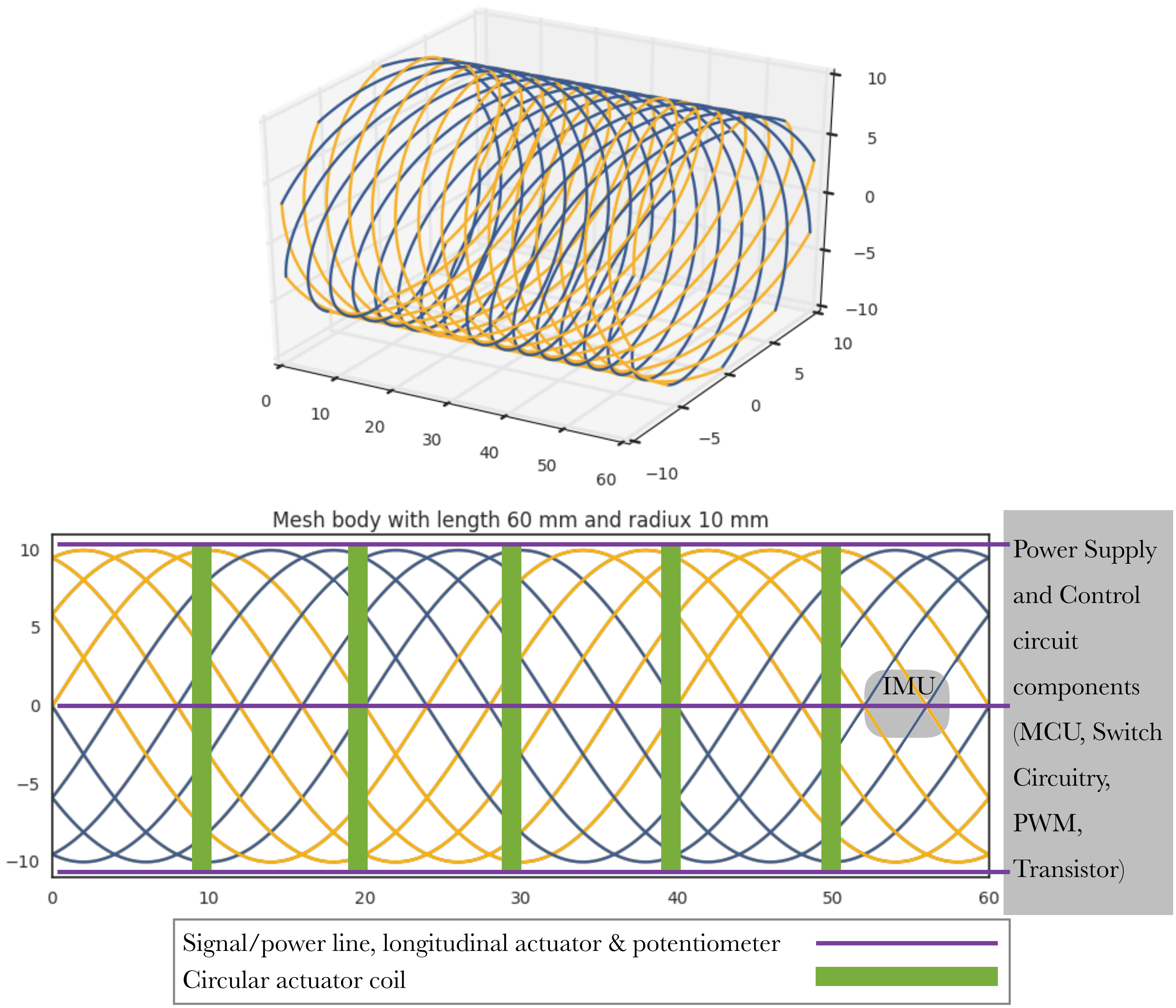

Fig.2 Mesh structure of the robot (length = 60 mm, radius = 20 mm)

We purchase the mesh, sensors, and other electronic components to used in this project. The nitinol actuators are not readily available, and the following steps are required to manufacture them.

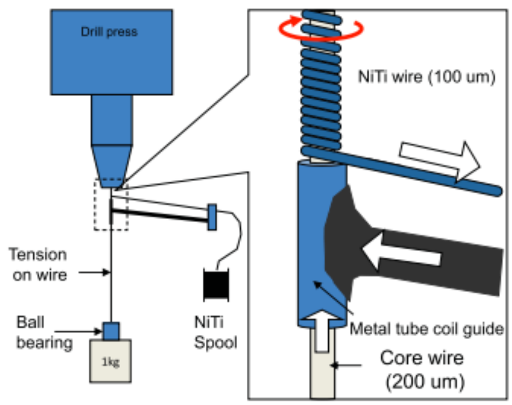

Fig.3 Nitinol actuator manufacturing process[7]

1. Wind up the nitinol wire around the center metal cable that is placed under tension using either a lathe or a drill press as shown in the figure.

2. Place the wind up wire (with the metal cable) under a 400 Celsius oven for 20 minutes. Remove the wires from the oven and let it cool down.

3. Remove the nitinol wire from the core wire.

C. Block Design

Control Unit

The control unit helps to realize the user commands within the capabilities of the robot. This is accomplished by a scheduling system and a feedback control loop that incorporates sensor datas to control the actuators. The feedback loop also monitors the condition of the circuitry and and helps to ensure the safety of execution.

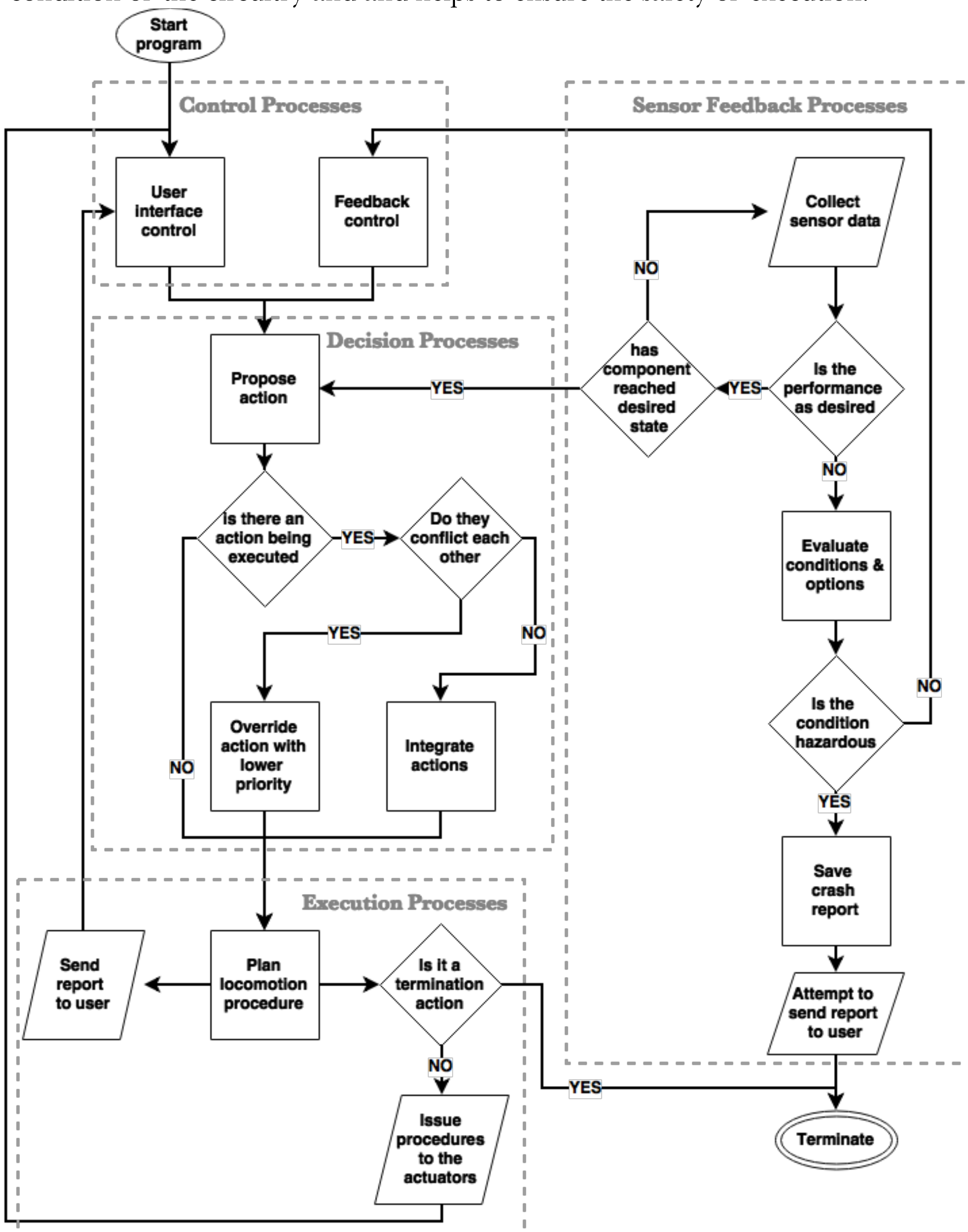

Fig.4 Software control flowchart

Actuation Module

The onboard control Unit communicates via serial communications with the control unit. It processes the commands sent from the computer, signals from the sensors, and and feedbacks from the actuation modules. It controls the behavior of the robot and sends feedbacks back to the computer regarding the status of the robot and the execution of commands.

- **The MCU** (**Micro-controller Unit**) receives the commands from the computer through the communication link. From command, the sensors information and its current state, it will use feedback control algorithm to send out control signal to manipulate the actuator accordingly. Some of the robot's movement will need micro-controller to execute signal in series. There are two main purpose to the control system. The first is to regulate the temperature of the NiTi actuator to an optimal temperature which would allow the reaction time of the actuator to improve. The second is to detect the orientation of the worm, correct it if possible and change the control orientation of the user. We use the PWM signal output of the MCU to drive the actuators via darlington transistor pairs. The power of the actuator will varies according to the duty cycle of the input signal.
- **The Driver Module** receive the control signal from the MCU and regulates the current supplied to the NiTi actuators.
- **NiTi Actuator**: There are two different types of actuation: longitudinal and circumferential. Both actuators are made from nickel titanium alloy (Nitinol) with the diameter of 200 microns that are wound around a cable to form a spring like shape. The resulted actuator will be place along the circumference of and length of the robot to form the muscle of the worm.
  - **Longitudinal Actuator** - The actuator expands and contracts the robot length.
  - **Circumferential Actuator** - The actor expands and contract the circumference of the section of the worm.
  - The two actuator move in sequence to create locomotion which moves the worm forward and change direction.

Sensor Module

The sensor module provide feedback input to the MCU to infer the state, position and orientation of the worm. There are two types of sensor in the sensor module:

- **Inertial Measurement Unit (IMU) -** The IMU tracks 9 degrees of freedom (3 translation, 3 rotational, 3 magnetic field). The MCU uses magnetometer to infer the orientation of the worm with by measuring the magnetic field of the earth. The IMU is also capable of measuring translation and rotational velocity but due to the worm's low velocity, the tracking error due to the drift is high
- **Band membrane potentiometer** - The band membrane potentiometers are attached to the worms body, horizontally along the actuator. These potentiometers are used infers the contraction length of the worm. The difference between the measurement from the potentiometer and the actual change (measured externally) will be compared, and the measurement will be compensated in the algorithm.

Power Module

The power module provide power to the control module and the actuator module. Both module has different requirement for power and has to be isolated from each other for safety. The power from the power module comes from a bench power supply

- **Power for control -** The raw power input goes to the 5V regular IC with a couple of capacitor to clean up the power signal for the control and actuator module.
- **Power for actuator -** The power of the actuator is the raw power (12V from the bench supply). The voltage regulation for the actuator is adjusted by changing the resistor that is in series with the actuator.

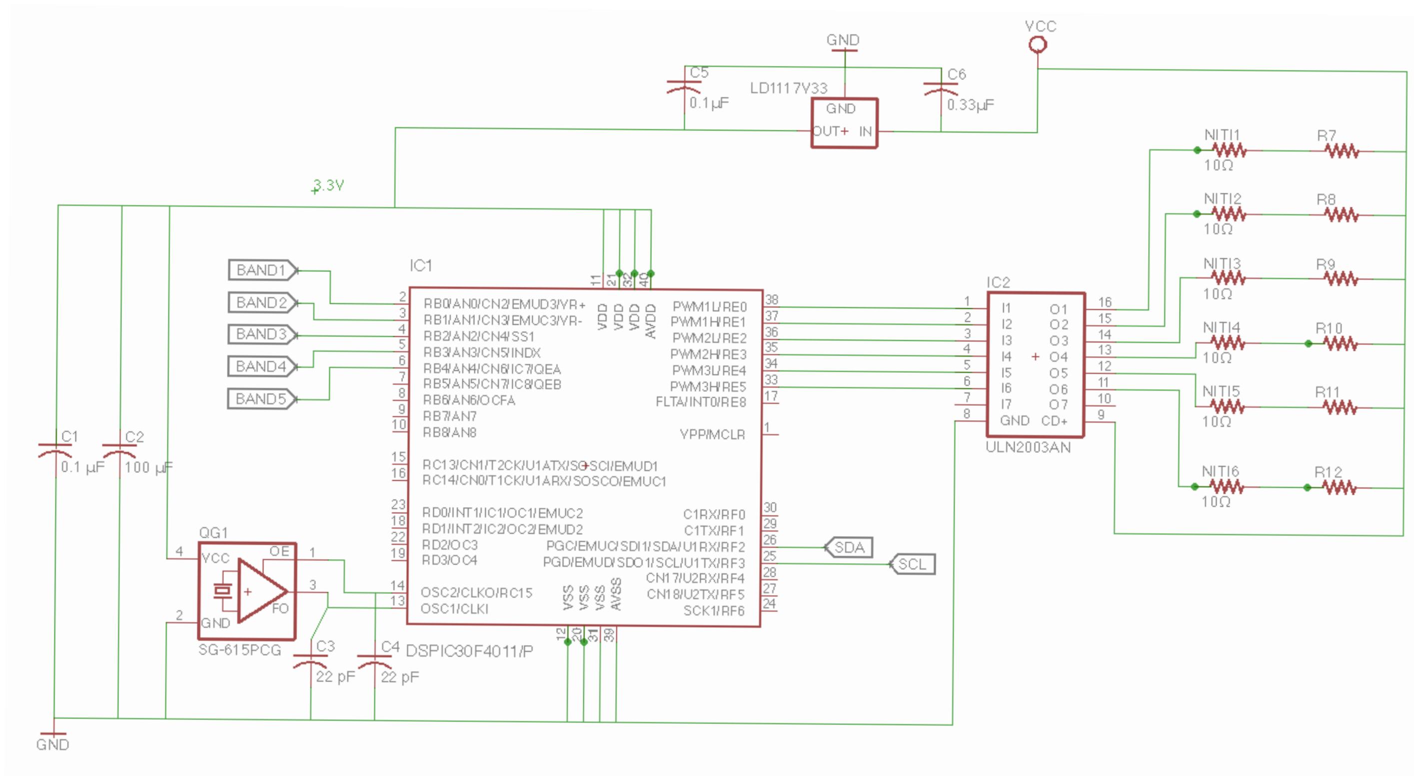

Fig.5 Schematics of the control, actuation and power module [2]

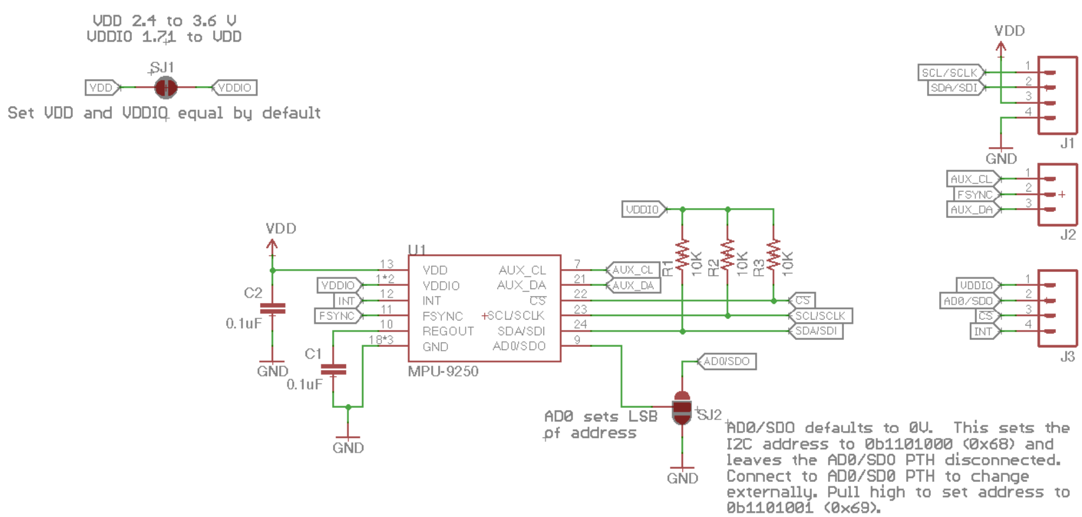

Fig.6 Schematics of the IMU from Sparkfun[10]

III. Requirements and Verifications

A. Project Requirements

Requirement	Quantification	Verification
Maximum movement speed	≥ 10 m/h	1.Drive the robot with the signal to achieve the highest velocity over a certain distance and measure the elapsed time. 2.use the elapsed time to calculate the speed.
Minimum turning radius of the body	≤ 0.5 meter	1.Command the robot to drive a concentric turn. 2.measure the turning circle and its radius optically.
Average cross-sectional weight	≤ 0.6 kg/m	Weight the robot and divide by length
Maximum inclination movement	≥ 10 degree	Drive the worm over an adjustable incline to see the maximum angle that it can climb.
Maximum longitudinal extension (from contracted form)	≥ 20%	1. Send the command to the robot to perform maximum extension. 2. Measure the length before and after the extension
Maximum circumferential contraction (from extended from)	≥ 10%	1. Send the command to the robot to perform maximum contraction. 2. Measure the circumference before and after the contraction.
Error in achieving the desired length for each spring structure segment in the NiTi actuator. (No external force)	±10% difference between actual and expected length	Measure the difference between the desired difference and the achieved distance, then construct distribution.

B. Modular Requirement

Control Module		
Requirement	**Quantification**	**Verification**
Sensor feedback response time	≤ 150 ms between sensor input and control output	1. Provide artificial input from a waveform generator, process the data with the algorithm, then output the data and measure both input and output with an oscilloscope. (Experiment for 1 minute.) 2. Verify that the average time difference between the two signals is less than 150 ms.
User input response time	≤ 150 ms between user input and control output	1. Attached an led to the output port of the MCU. 2. Press a button on the computer to send a command that will light up the led. 3. Use a slow motion camera to measure the time difference between the moment the key is pressed and the moment the led lights up.

Actuator		
Requirement	**Quantification**	**Verification**
Maximum body extension (longitudinally)	≥ 20% body length	1.drive all the actuator with the maximum current that the actuator can handle before permanent deformation 2.Measure the length before and after.
Maximum body contraction (cross-section)	≥ 10% body circumference	1.drive all the actuator with the maximum current that the actuator can handle before permanent deformation 2.Measure the circumference before and after.
Driver module	able to drive all actuator at 200mA peak-to-peak with 50% duty cycle over 30 minutes.	1. Send the command to the robot to generate a 200 mA peak-to-peak signal to drive the nitinol actuator. 2. Wait for a period of 30 minutes or until the transistor stop working. 3. Verify that the driver module is still operational after cooling down.

Sensor		
Requirement	**Quantification**	**Verification**
Band membrane potentiometer accuracy	±10% horizontal extension measurement	1. Send the command to the robot to perform maximum extension. 2. Measure the length before and after the contraction. 3. Use the band variable resistor to infer the length before and after the contraction. 4. Verify that both inference is within 10% of the actual length.

Power		
Requirement	**Quantification**	**Verification**
Power regulation	Able to provide 2.7 V to 3.8 V to onboard chips for 30 minutes	1. Drive the circuit with simulated commands for several 30 minutes intervals, and monitor the circuit voltage. 2. Verify the expected voltage is provided.
Power supply	Able to provide 4 W to the actuators for 30 mins	1. Drive the power supply with adequate load (or the actuators themselves) repeatedly for several 30 minutes intervals, and monitor the circuit. 2. Verify the expected power is provided.

IV. Tolerance Analysis

The suitable operation range and condition of the robot concerns the following major aspects: operation temperature, fatigue, and linear velocity.

A. Operation temperature

The nitinol actuator operate on a very small temperature range. The nitinol actuator expands and contracts by transforming the state of its molecule into either Martensite(expansion state) or Austenite(contraction state). A precise measurement of these transformation is needed for precise control. The specific temperature will be accompanied by the final deliverable, incorporated into the control system, and should be kept in mind during operation. In addition, the nitinol actuators will start to lose their memorized shapes when heated over 250 °C, and this will be the absolute maximum operational temperature of the robot. The chips, though not part of the robot itself, has a minimum operational temperature of -20 °C, and this will be the absolute minimum operational temperature of the project.

B. Fatigue

The nitinol actuators subject to a certain degree of permanent deformation after each actuation. The exact deformation rate is determined by the characteristics of the nitinol spring, which is largely influenced by the temperature the coil is annealed at. MIT discovered that springs annealed below 400 °C will exhibit a consistent deformation of around 5% of the original austenite state length given with actuations of 350mN force, with repeated usage [7]. Springs annealed at greater temperatures however, will tend to fatigue quicker and lose the shape memory properties. At the same time, increasing the annealing temperature increases the detwinning force, resulting in better capabilities for the wires to retain their shapes. Therefore, an annealing temperature around 400 °C will optimize the tradeoff between efficiency during operation and long term fatigue effects.

C. Linear velocity

The linear velocity v of the robot is controlled by the horizontal length increment of the mesh body produced by each compression l, the number of compressions going on at once n, and the rate of compressions f : $v = l\,n\,f$

The following calculation determines the half horizontal length increment Δa of each of the rhombi on the mesh [11].

β = angle between the side of the rhombus and the horizontal axis
$t = l_0 \sin\beta$ = ½ length of the vertical axis of the rhombus
l_0 = length of the side of the rhombus
C = Circumference of the Mesh
ΔC = Compression alone the circumference of the Mesh
a = ½ length of the horizontal axis of the rhombus
$\delta = \frac{\Delta C}{C} l_0 \sin\beta$ = compression per ½ rhombus

$$t - \delta = l_0 \sin\beta'$$

$$\sin\beta' = -\frac{l_0 \sin\beta - \delta}{l_0} = \sin\beta - \frac{\delta}{l_0}$$

$$a' - a = \Delta a = l_0(\cos\beta' - \cos\beta) = l_0 \cos\left(\sin^{-1}\left(\sin\beta - \frac{\delta}{l_0}\right)\right) - l_0\cos\beta$$

$$= l_0 \cos\left(\sin^{-1}\left(\sin\beta - \frac{\Delta C}{C}\sin\beta\right)\right) - l_0\cos\beta$$

The rate of compression f is capped by the rate for the nitinol actuator to complete a cycle of transformation. This will need to be determined experimentally.

The number of compressions at one time is limited by the number of separately controlled actuators and the flexibility of the mesh. Given a fixed total length of the worm, at most N-1 actuators can be contrasting at the same time, where N is the total number of actuators. However, depending on how much the mesh can be expanded on the vertical axis, this may not be possible. Our design will start with 1 actuator per compression, while trying to maximize l in order to maximize v.

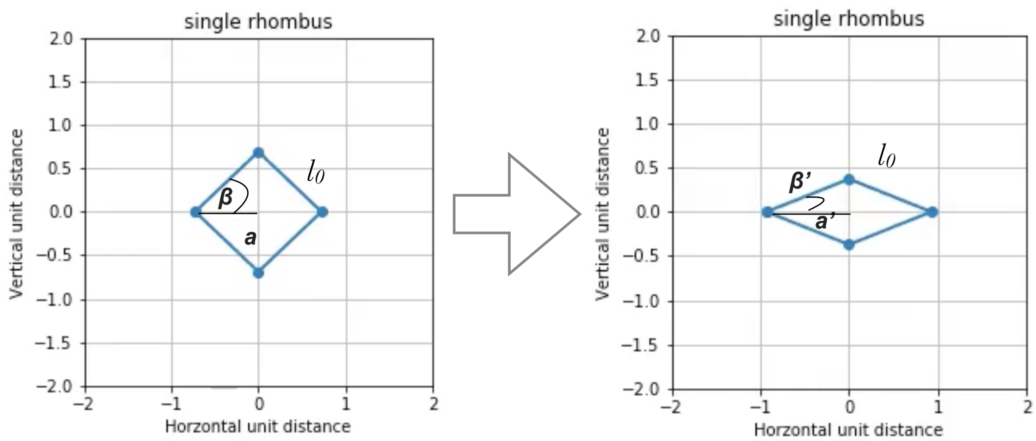

Fig.7 Illustration of a single rhombus section

The compression along the circumference ΔC is determined by the force required to contract the mesh, the shear strain of the spring, among other factors listed below. We determine the compressed circumference of the mesh, use it to determine the length of spring in austenite, and subsequently, the length it will extend when transferred into martensite. The formula for the length extension is:

$$l = free\ length + detwinning\ in\ martensite - detwinning\ in\ austenite$$

$$= \frac{\pi \gamma D^2 n}{d\kappa} + \frac{8FD_{eff}^3 n}{G_m d^4} - \frac{8FD^3 n}{G_A d^4}$$

δ = πγD2n/(dκ)

δ = Free Length difference between martensite and austenite for a NiTi coil

γ = shear strain of the spring

n = number of active coil in the spring

D = spring diameter`

d = diameter of the NiTi wire

κ = stress correction factor from Wahl's formula [5]

V. Cost Analysis

Distributor	Items	Quantity	Cost per unit	Total
Digi-key.com	Darlington transistor: ULN2003A	4	$0.50	$2.00
Dynalloy, inc	Flexinol Acutator Wire	30	$1.37	$41.10
ECE Shop	PCBs	3	$4.70	$14.10
McMaster Carr	PEEK mesh	4	$30.81	$123.24
McMaster Carr	Nitinol Wire	30	$1.19	$35.70
Microchip	PICkit 3 In-Circuit Debugger	1	$47.95	$47.95
Mouser.com	Microcontroller: DSPIC30F4011-30I/P	4	$6.84	$27.36
Mouser.com	Clock Oscillator: SG-615P	4	$2.25	$9.00
Mouser.com	Passive Elements (Resistors, Capacitor, etc)	1	$10.00	$10.00
Sparkfun	SoftPot Membrane Potentiometer 50mm	5	$4.95	$24.75
Sparkfun	IMU: MPU-9250	2	$14.95	$29.90
Parts Sub-total			**$125.51**	**$365.10**
Service	**personal**	**Hours**	**Hourly rate x2.5**	**Total**
Computer Engineer	Kunakorn Puntawong	225	$100.00	$22,500.00
Computer Engineer	Zehua Li	225	$100.00	$22,500.00
Labor			**$200.00**	**$45,000.00**
Grand Total				$45,365.10

The grand total is the sum of the parts cost and the labor cost. The labor cost is made with an assumption that a computer engineering undergrad makes $40/hr.

VI. Schedule

Week of	Event	Kunakorn	Zehua	Team
2/20/17	Design document due by Friday 24, 2017 Midnight	Works out the mathematics and physics behind the nitinol actuator. Start prototype the control and power moduel on eagle.	Create simulation for the mesh expansion and contraction. Contact manufacterer to purchase parts for the actuator module	Begin Purchasing parts to build nitinol actuator and control modules. Start prototyping power and control module on breakout board
2/27/17	Design document review Wednesday March 1, 2017 at 9:30AM	finish prototyping the control and power module on eagle. Start debug the circuit schematics on breakout board	Test out the nitinol wire that the machine shop made and attemp to make improvement toward the actuator. Start debug the circuit schematics on breakout board.	Test out the property of the nitinol wire received from the machine shop. Finish prototyping the power and control module.Make final touches on design for design review. Purchase all parts
3/6/17	Soldering assignment due Friday March 11, 2017	Finish debugging the circuit schematics. Start on experimenting IMU and write the open-loop control program	Purchase various types of mesh that could be capable with the actuator. Work on interface of the MCU.	Send the power and control module circuit schematics out to the electronics shop to manufacture PCB. Start experimenting with IMU and purchase mesh
3/13/17		Experiment to find the best mesh out of all the purchased ones. Finish writing the open-loop control program.	Finish the interface program of the MCU. Start writing out the program for the locomotion control of the worm.	Test out various mesh with the actuator. Send the rest of the nitinol wire to be mass produced at the machine shop. Start writing out the program for locomotion control
3/20/17		Start assembling the first worm robot. Perform verification and test on the earthworm.	Star assemlbing the first worm robot prototype. Fine tune the locomotion control algorithm with the earthworm robot prototype.	Start Assemble the first worm robot prototype and perform verificaiton tests. Run the locomotion code and start fine tuning the locomotion.
3/27/17	Individual progress reports due Monday March 27,2017	Experiment with various actuator arrangements. Finalize the circuit schematics and PCB layout.	Experiment with various actuator arrangement. Finalize the worm robot design.	Assemble the final worm design. Improve the algorithm for locomotion.Send out the final PCB to the service shop
4/3/17		Finish anything that is left out and uncompleted	Finish anything that is left out and uncompleted	Improve the algorithm.
4/10/17		Assemble the final mesh and actuator design. Assemble the final robot prototype	Solder every component onto te PCB. Assemble the final robot prototype	Solder every component to the final PCB. Finish the project.
4/17/17	Mock Demo	Fine tuning and adjusments	Fine tuning and adjusments	Fine tuning and adjusments
4/24/17	Demonstration	Prepare for demonstration.	Prepare for demonstration	Fine tuning and adjusments
5/1/17	Final Paper and Lab notebook due	Prepare for the final presentaiton	Prepare for the final presentation	

VII.Ethics and Safety

A. Ethics

Abiding to the IEEE Code of Ethics [4], there are a few duties we need to fulfill. We will provide sufficient safety mechanisms (insulation to shock and heat, regulations) and safety warnings regarding any utilization of power source and batteries.

Complying with Code of Ethics, we will also provide specifics regarding the requirements of proper power/battery setup, and a estimation of performance on different terrain in case the device will be used in an out door environment or in different regions of the world.

The device has a rather large scope and we welcome all criticism and suggestions to its improvements and regarding its flaws. If circumstances where specific modification or improvement are required, we are responsible to provide assistance. Similarly, we welcome any inquiries regarding the research process and any specific aspects.

Our software design and implementation will abide to the ACM Code of Ethics and Professional Conduct [1]. The control system and algorithms draw inspirations from various previous works and we will "honor property right including copyrights and patent, and give proper credit for intellectual property." Similarly, we will keep an open altitude towards future projects., document the engineering process and provide references to replicate any experimentations and to facilitate further improvement of designs and implementations

B. Safety

Nitinol actuator

The nitinol actuators are essentially live wires, and should be dealt properly in a safe manner. The maximum current that we are working with is lethal 0.6 Amps and should be handled with proper insulation and safety protocols (such as work with the circuit on top of thick rubber mat, with rubber gloves, and deploy the one hand rule). Any form of experimentation and operation should never be done alone with the assembled structure. The maximum calculated temperature that the nitinol wire can reached from the power regulator is 60 Celsius so it is safe for the human skin.

Soldering

Soldering is knowledge that is required for any ECE students. As the solder temperature can get upward of 200C , we have to to use clamps to hold the board and component to prevent any jittering. Also, fan and fume extractor will be use at all time to ensure clean air flow.

Hot glue

Hot glue gun can be dangerous if not used properly. So, these are some of the few rules and measure that will be follow:

- Wear safety glass at all time even when not using the hot glue
- Never touch the heating element of the hot glue
- Do not leave hot glue gun attended

VIII.References

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