

Robot Metabolism: Truss Link

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INTRODUCTION

Biological organisms operate as open systems: They absorb material from their environment and expel waste. This process is the basis for the long-term resilience of biological organisms over their lifetime. Progress in artificial intelligence has advanced robots' ability to adapt by learning new behaviors, but has left the robots' physical morphology fixed and monolithic. Typical robots today cannot increase in size and complexity, adapt, or self-repair. In contrast, biological lifeforms developed the ability for physical adaptation, repair, and replication, including absorbing and expelling material, long before any form of intelligence ever emerged. In light of that, artificial intelligence, although important, may just be one piece of the puzzle of true robot autonomy: robot self-sufficiency. For robots to become resilient and sustainable in the long term, we must develop processes that allow them to act as open systems and develop physically by consuming, expelling, and reusing material from their environment. We call this process robot metabolism.

Unlike traditional robot manufacturing processes, where robots may be involved in the process of making robots in a variety of ways, a robotic adaptation process qualifies as robot metabolism if it satisfies two criteria: First, robot metabolism cannot rely on active physical support from any external system to accomplish its growth; the robot must grow using only its own abilities. The only external assistance allowed is that which comes from other robots made of the same components. Second, the only external provision to robot metabolism is energy and material in the form of robots or robot parts. No new types of external components can be provided. In the case of the platform used in this work, material comes in the form of robot modules and energy in the form of electricity stored in each module's batteries.

The concept of robot metabolism raises more questions than we can answer here. Thus, we focused on a set of key challenges: self-assembly, self-improvement, recombination after separation, and robot-to-robot assisted reconfiguration. In this work, we demonstrate the potential of this approach and introduce a robot platform capable of achieving it. We believe that this is the first demonstration of a robot system that can grow from single parts into a full three-dimensional (3D) robot, while systematically improving its own capability in the process and without requiring external machinery.

The choice of robotic building blocks is key as it spans the ultimate space for all possible designs. Biological lifeforms comprise only about 20 amino acids assembled into polypeptides during protein synthesis, ultimately giving rise to innumerable proteins and millions of self-sustaining lifeforms. Similarly, modular robots constructed from a finite set of simple, standardized components give rise to diverse functional structures and adaptive mechanisms. We believe that imitating nature's methods, rather than merely its results, will lead more fundamental innovation in robotics. Replicating animals and humans in the form of robot dogs and humanoid robots is ultimately limiting. Thus, the robot building blocks need to be designed with the capacity for robot metabolism. Once developed, platforms capable of robot metabolism provide a physical counterpart to self-improving artificial intelligence. Thus, we open the possibility of robots changing their own form to ultimately overcome the limitations of human ingenuity.

We introduce the Truss Link, a robot building block designed to enable robot metabolism. The Truss Link is a simple, expandable, and contractible, bar-shaped robot module with two free-form magnetic connectors on each end. Animating any structure, Truss Links form robotic "organisms" that can grow by integrating material from their environment or from other robots (see fig). We show how two substructures can combine to form a larger robot, how 2D structures can fold into 3D shapes, how robot parts can be shed and then be replaced by another found part, and how one robot can help another "grow" through assisted reconfiguration.

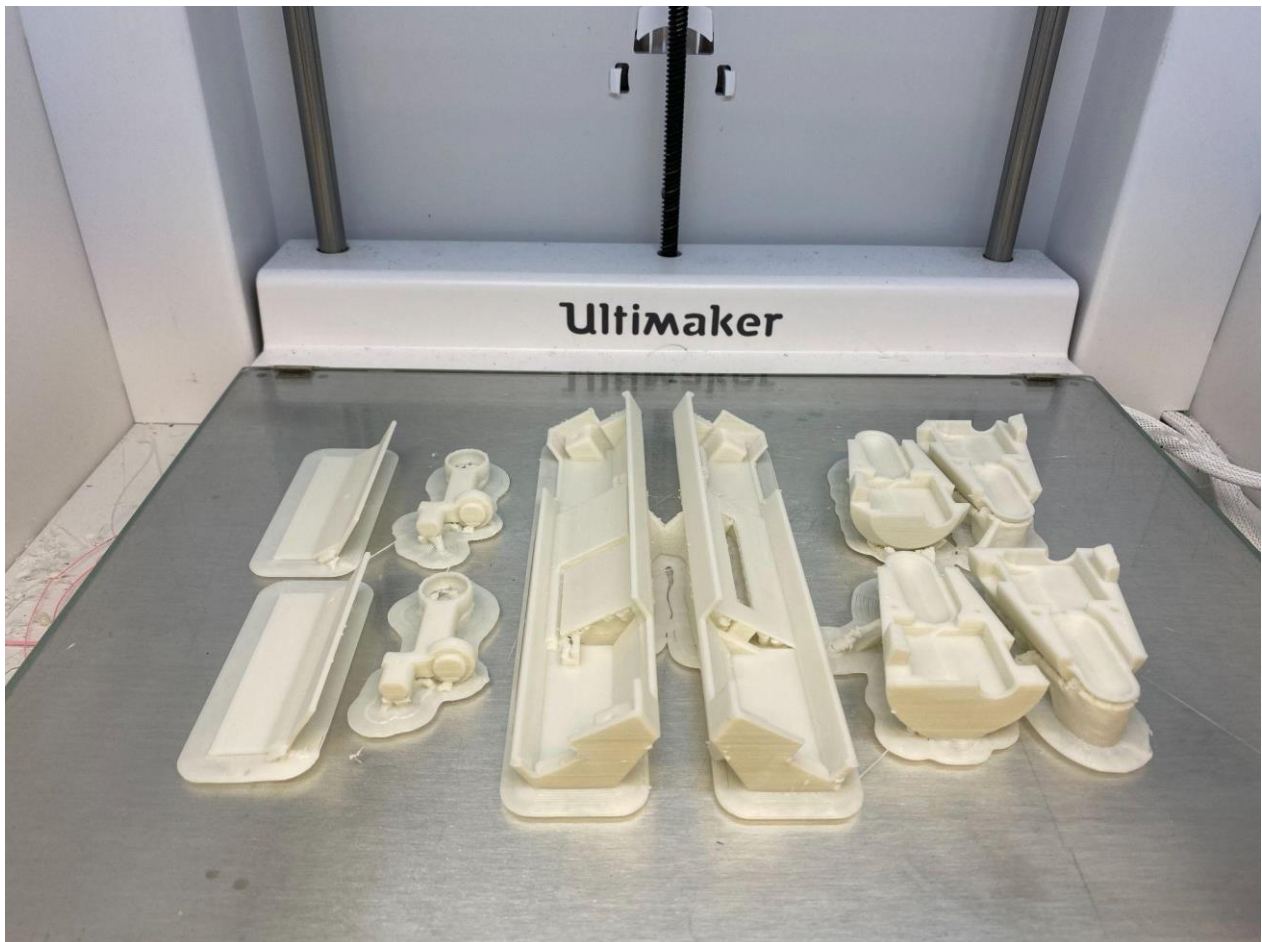


Fig. 1. Robot metabolism allows machines to “grow.”

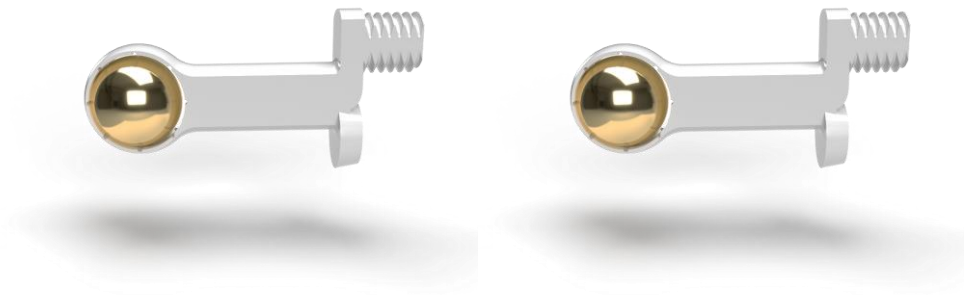
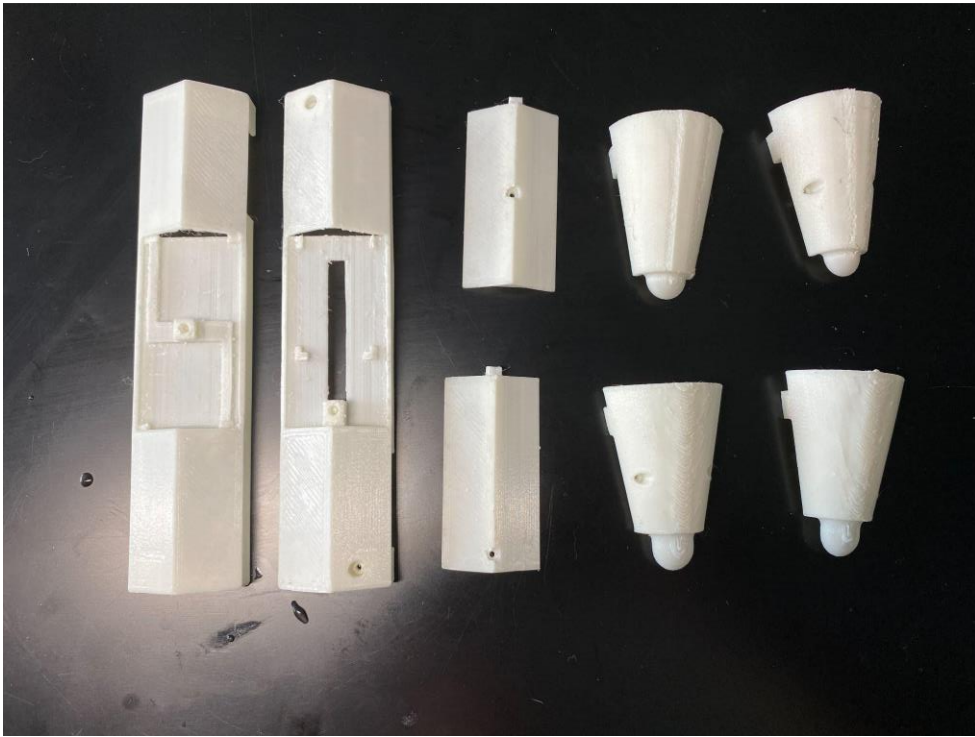
Robot modules can grow by consuming and reusing parts from their environment and other robots. This ability, essential to biological lifeforms, is crucial for developing a self-sustaining robot ecology. This paper demonstrates the above developmental sequence in detail: from individual modules to a fully assembled ratchet tetrahedron robot.

3D Printing Components

1. Download CAD files for the shell and connectors from below link:
3D Files can be found in the 3D_files folder.
2. Use Glow-in-the-Dark filament 3mm with Ultimaker S5
3. Adjust Ultimaker S5 to following setting by using cura:
 - a. Use Core CC 0.6
 - b. Set quality layer height as 0.2
 - c. Set printing temperature,initial printing temperature and final temperature as 215 C,
 - d. Change Flow as 120%
 - e. Change print speed and initial layer speed to 40 mm/s
 - f. Change retraction distance to 5mm/s
 - g. Turn Z Hop When Retracted on
 - h. Use tree support with Gyroid shape and limit degree as 45 degree
 - i. Use Brim for build plate adhesion



4. Use sandpaper to smoothen out any uneven print surfaces



Build Preparation

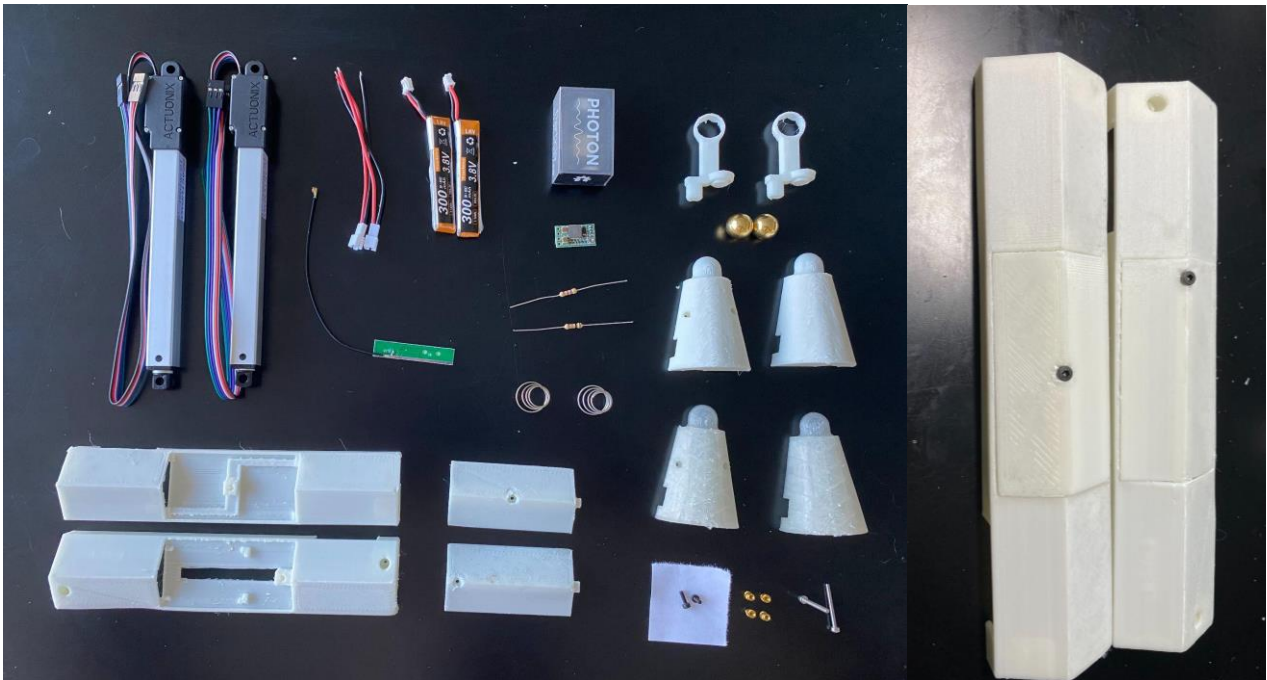
Partlist

Truss Link Body

1. 3D printed Body-Shell (Top & Bottom) and 2 x Cover
2. 2 x Actuator L-12I
3. Particle Photon
4. 2.4GHz Mini Flexible WiFi Antenna with uFL Connector - 100mm
5. Drok Voltage Regulator
6. 4.7 kOhm Resistor
7. 10 kOhm Resistor
8. 2 x JST-PH 2.0 Female harness
9. 2 M2x20 Stainless Steel flat head screws
10. 2 M2x8 Carbon steel flat head screws
11. 4 x M2 heat set insert

Truss Link Connector

1. 2 x 3D printed Connector-Shell (Top & Bottom) and Magnet Holder
2. Confined-Space Conical Compression Spring 0.75" L, 0.6" x 0.375" OD
3. Neodymium magnet sphere 1/2" diameter
4. 2 M2x8 Carbon steel flat head screws
5. 2 x M2 heat set insert

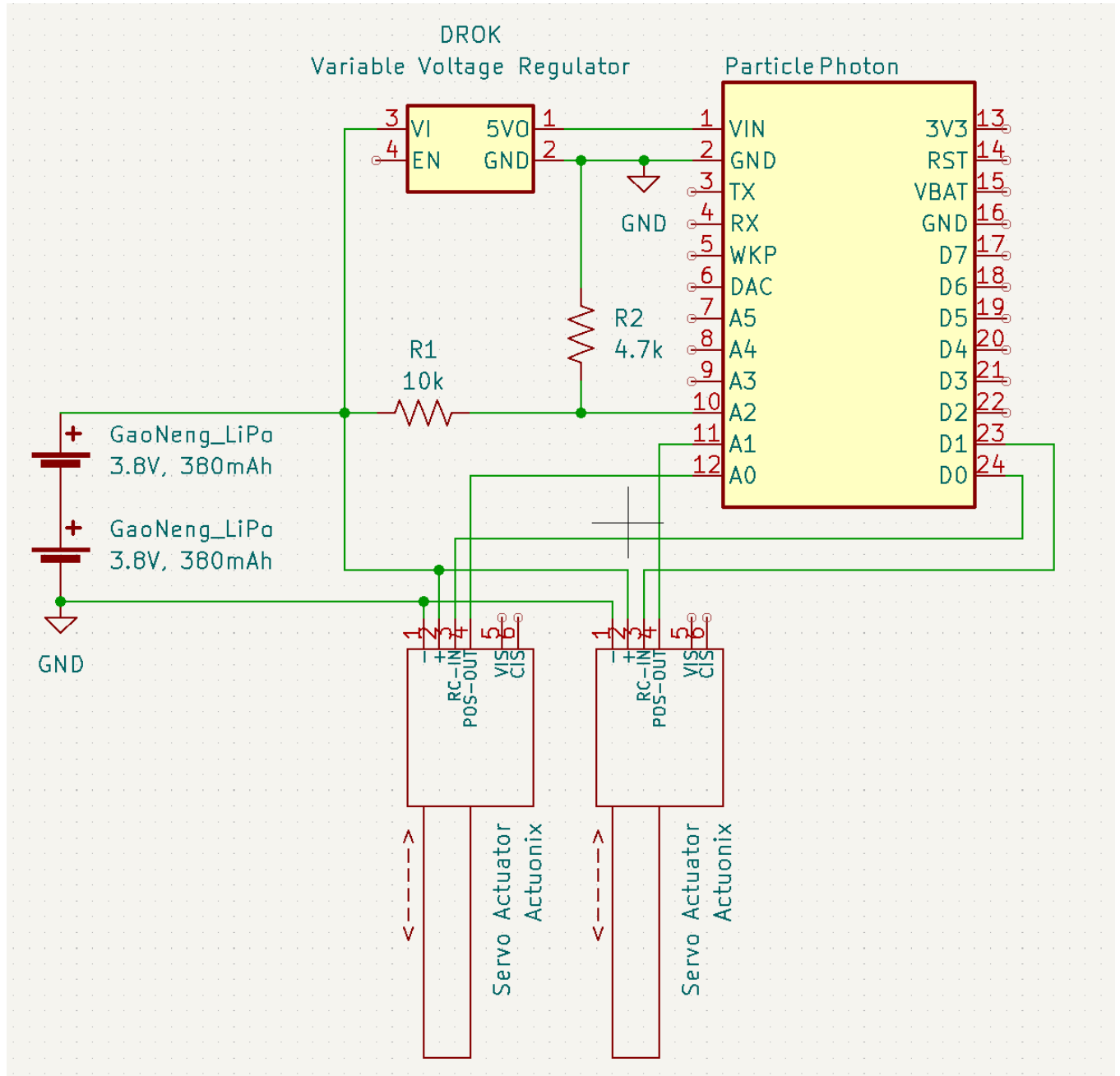


Support Material:

1. Electrical tape
2. Heat Shrink tube
3. AWG 26 Wires



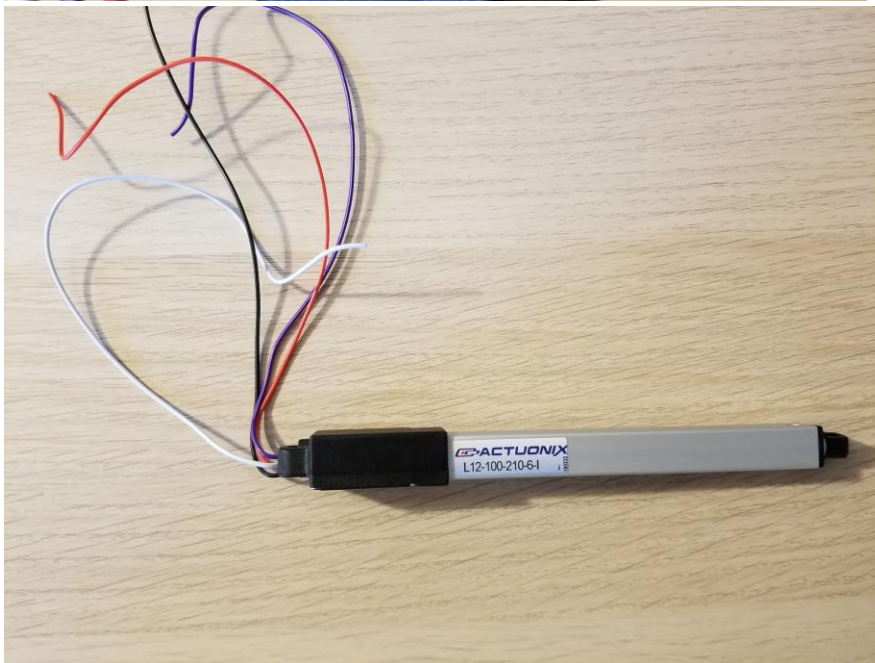
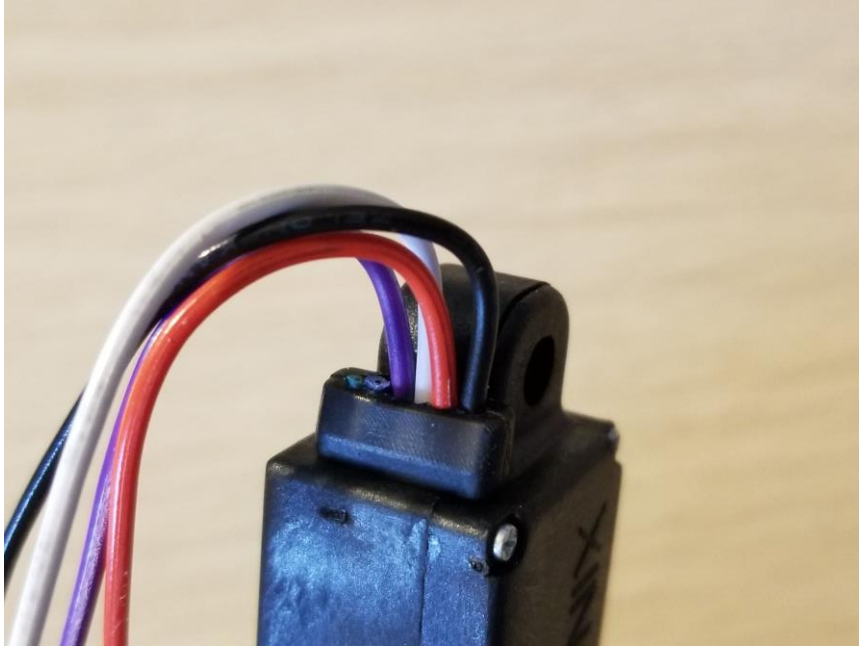
Circuit Diagram



Getting the Components Together

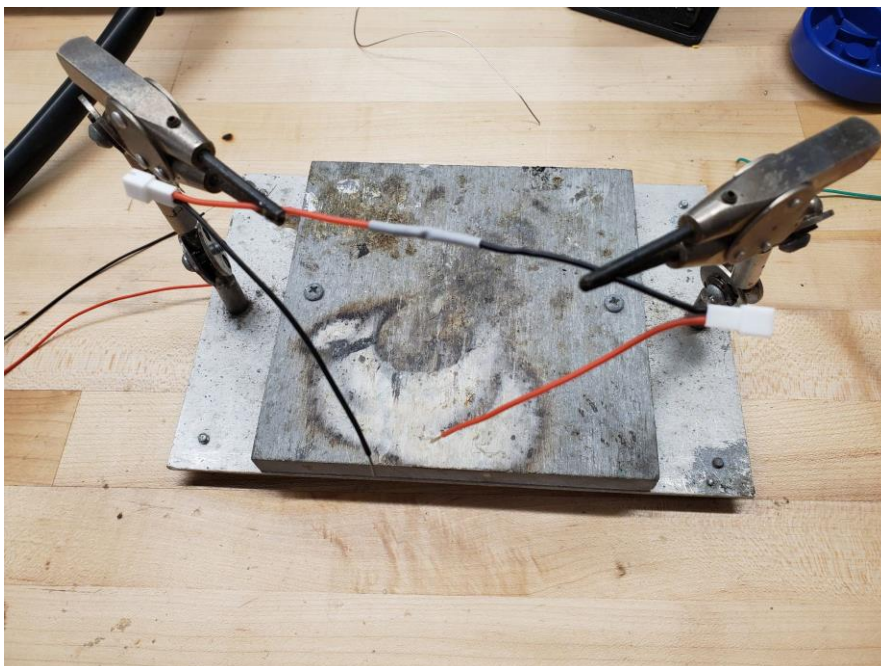
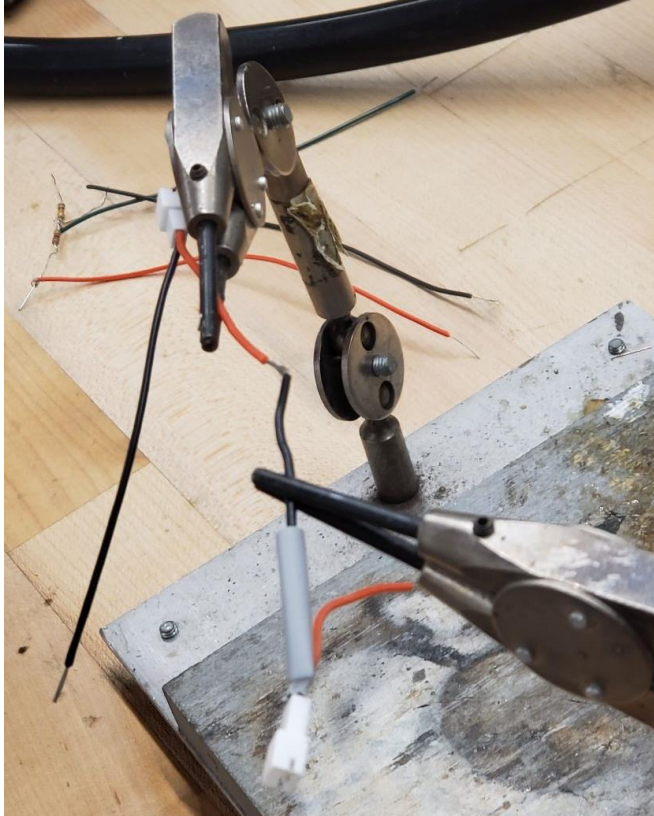
Actuators

1. Cut green and blue wires flush with the actuator housing and save them for future use. For the rest of this assembly, we will only be using these wires.
2. Separate the remaining 4 wires (black, red, white, purple).
3. Cut the red and black wires in half for future use.



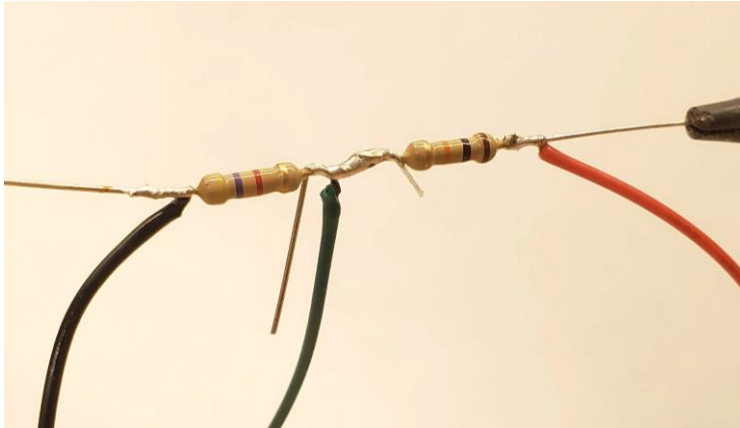
Battery Harness

1. Cut the red wire from one JST-PH 2.0 Female harness and the black wire of the other JST-PH 2.0 Female harness to 5cm in length.
2. Put heat shrink tubing around one end of the wires to be soldered.
3. Solder the shortened red wire from one JST-PH 2.0 Female harness to the shortened black wire of the other JST-PH 2.0 Female harness.
4. Heat the tubing so it conforms to the wires.



Voltage Divider

1. Cut green wire as 100mm, red wire as 100mm and black 50mm (tolerance: ± 5 mm).
2. Solder the resistors and wires as per the circuit diagram (red wire to 10 kOhm, black wire to 4.7 kOhm and green in the middle).
3. Arrange the wires such that the green and black wires are on one side and the red wire is on the other.



4. Clip all excess wire and sharp corners to prevent them from puncturing the heat shrink.



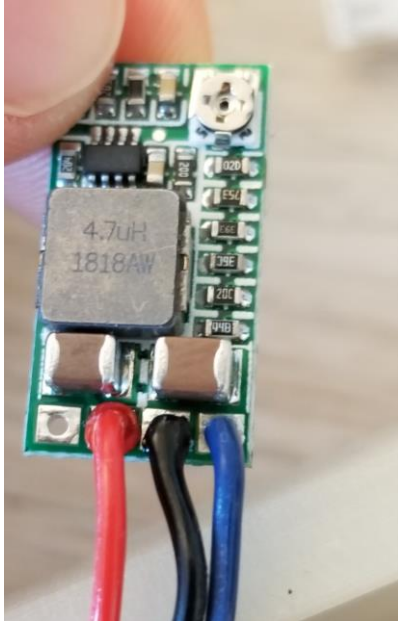
5. Pull heat shrink tubing over the soldered resistors.



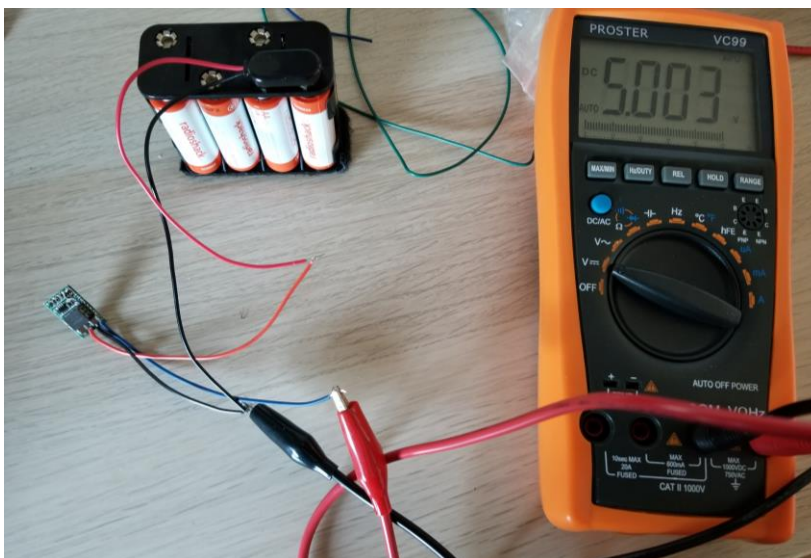
6. Heat the tubing so it conforms to the wires and resistors.

Voltage Regulator

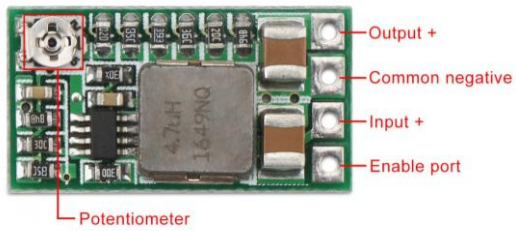
1. Red Wire 45mm, Black wire 110 mm and Blue wire 135mm (tolerance: +-5mm)
2. Solder the blue wire to the VO+ port.
3. Solder the black wire to the GND port.
4. Solder the red wire to the IN+ port.



5. Connect the red wire of the combined JST-PH 2.0 Female harness to the red wire of the Voltage Regulator
6. Connect the black wire of the combined JST-PH 2.0 Female harness to the black wire of the Voltage Regulator
7. Connect the black prong of the Multimeter to the black wire of the Voltage Regulator
8. Connect the red prong of the Multimeter to the blue wire of the Voltage Regulator
9. Connect the batteries to the female harness to apply between 7-9V DC
10. Turn on Multimeter and set the read setting to DC Voltage

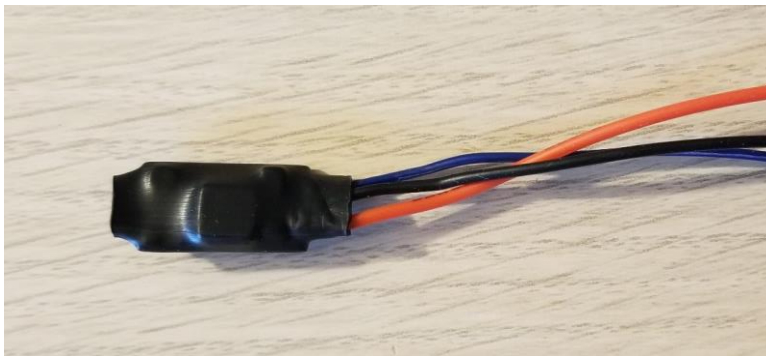


11. Adjust Voltage Regulator potentiometer with Philips screwdriver to make the output to 5V



12. Pull heat shrink tubing over the voltage regulator.

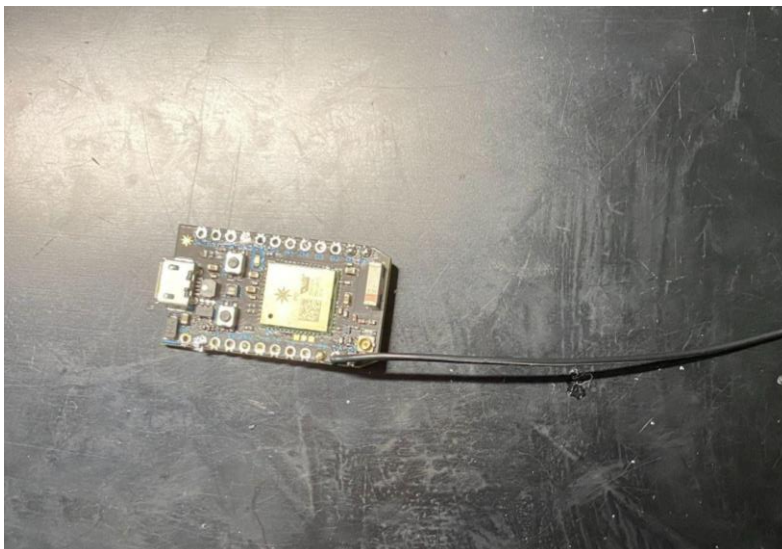
13. Heat the tubing so it conforms around the voltage regulator.



Particle Photon

Note: This step can be deferred until later in the assembly process to better help gauge the wire lengths

1. Solder the black wire (100mm) on the GND port.



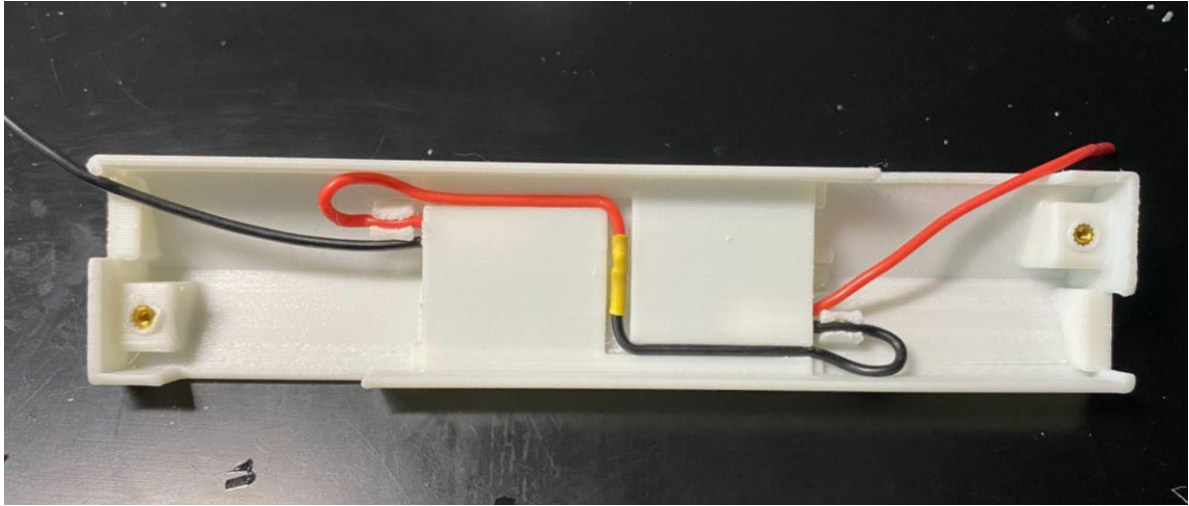
Truss Link Body Assembly

Heat Set Insert into shell:

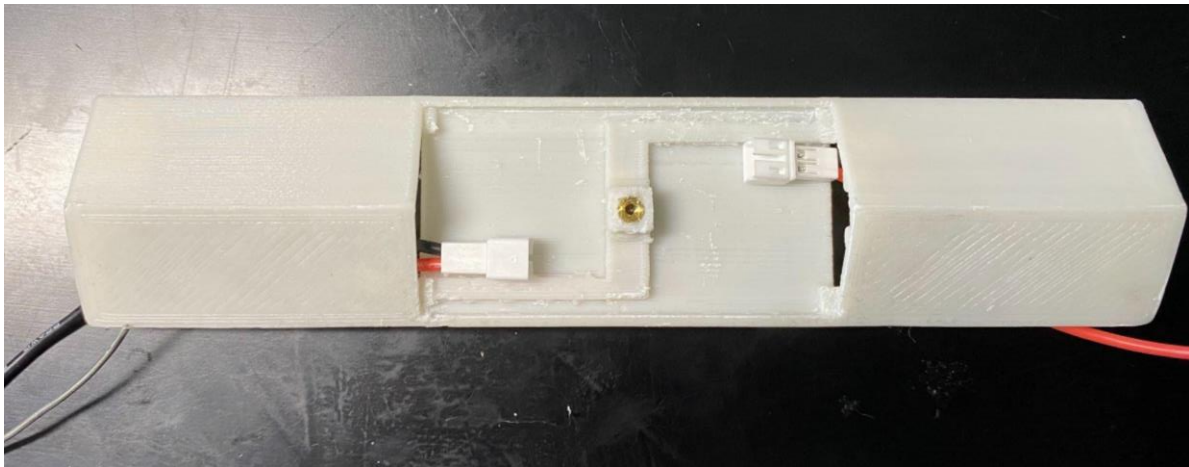
1. Increase electrical soldering gun temperature to 300°C
2. Use a heat gun, press the heat insert into the body shell, double check if any 3d material is left inside of the heat insert, you will not be able to thread screw in if there is too much material inside of the nut.

Place battery wire into body shell:

1. Place battery wire into wire channel and push the wire into wire hook

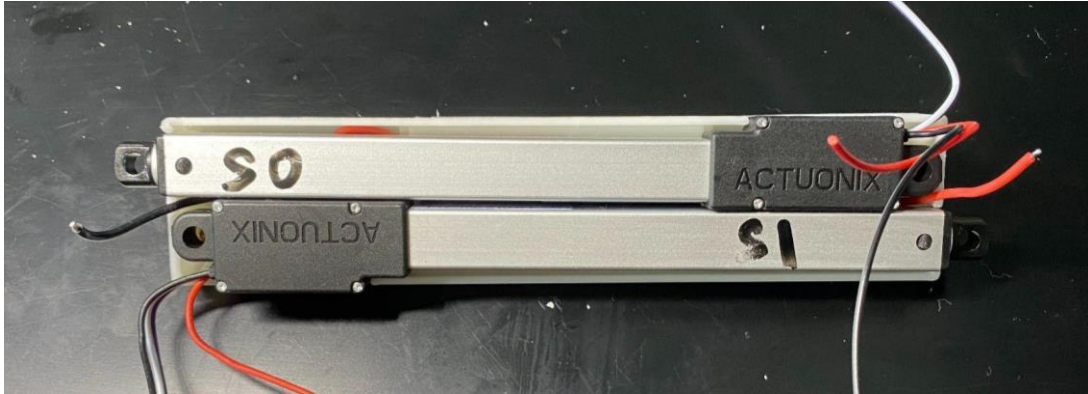


2. Place battery and test if there is enough space for the battery, otherwise, adjust the wire location.



Actuator into shell

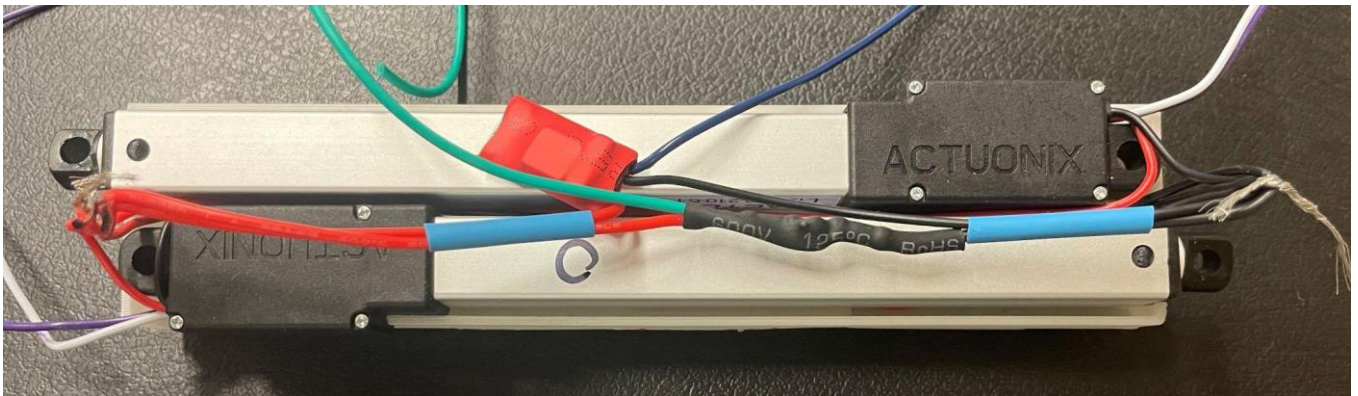
1. Before placing the actuator into a 3D printed shell (battery side), Stick electrical tape to cover the gap between two actuators.
2. Pull red and black battery wire in the end of the shell and make sure the two wires do not interference with the actuators.



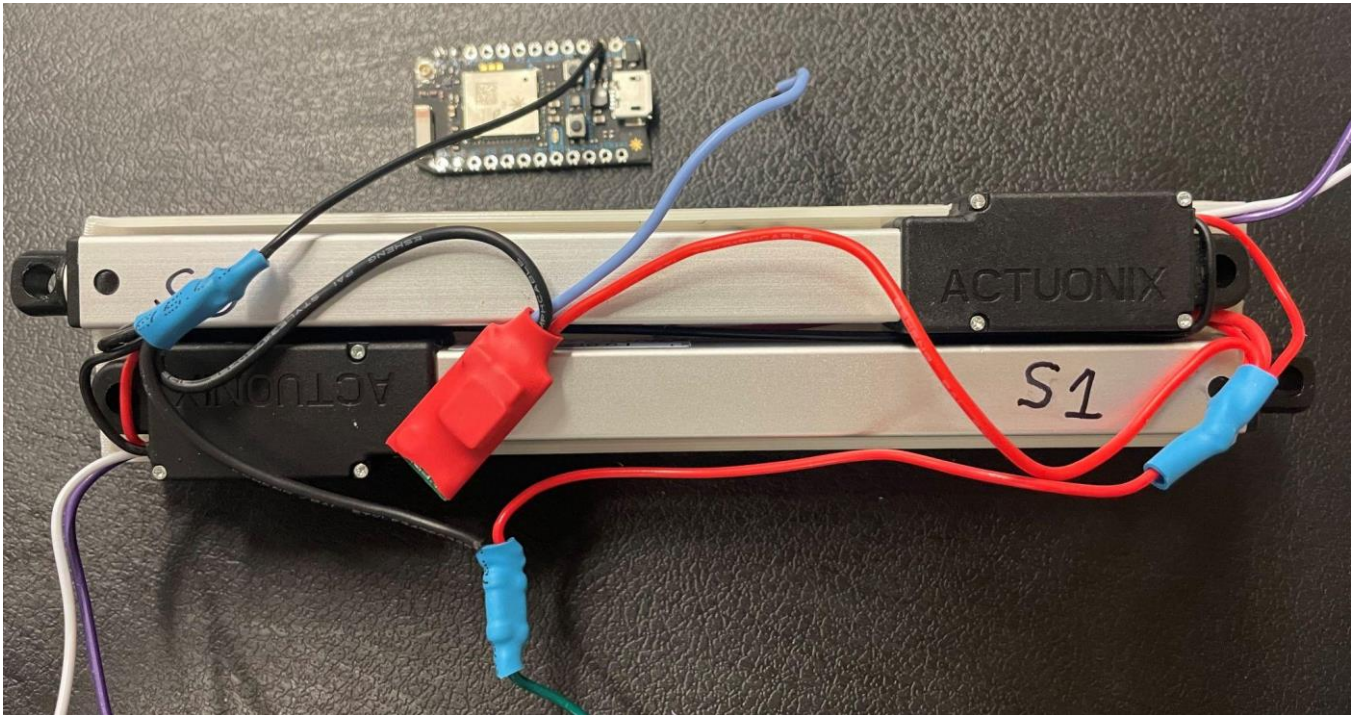
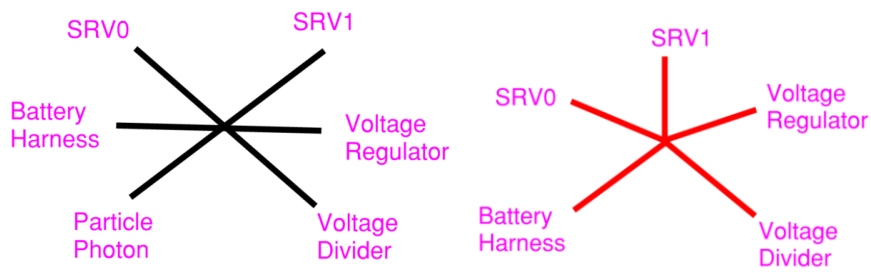
3. Cut Servos' wire following below table: (tolerance: ± 5 mm)

	Black Wire	Red Wire	White Wire	Purple Wire
Servo 0	160mm	65mm	140mm	140mm
Servo 1	65mm	160mm	100mm	100mm

4. Push Servo 0 black wire and Servo 1 red wire into the mid-gap between two actuators. We will place all back (ground) wires on the Servo actuator 1 side and all red (positive) wires on the Servo actuator 0 side.
5. Place voltage regulator on the end of Servo 1 and place resistances on the end of Servo 0. Use Electrical Tape to hold VR and R on the actuators.
6. Make sure all red (Pos) wires and all-black (GND) wires stay together.
7. Place the blue wire from the voltage regulator on servo 1 side.



8. Solder the remaining loose black and red wires as per the Circuit Diagram. Use the below images as reference.
 - a. Remember to place heat shrink around one of the wires before soldering. Once soldered, heat the tubing so it conforms to the wires.

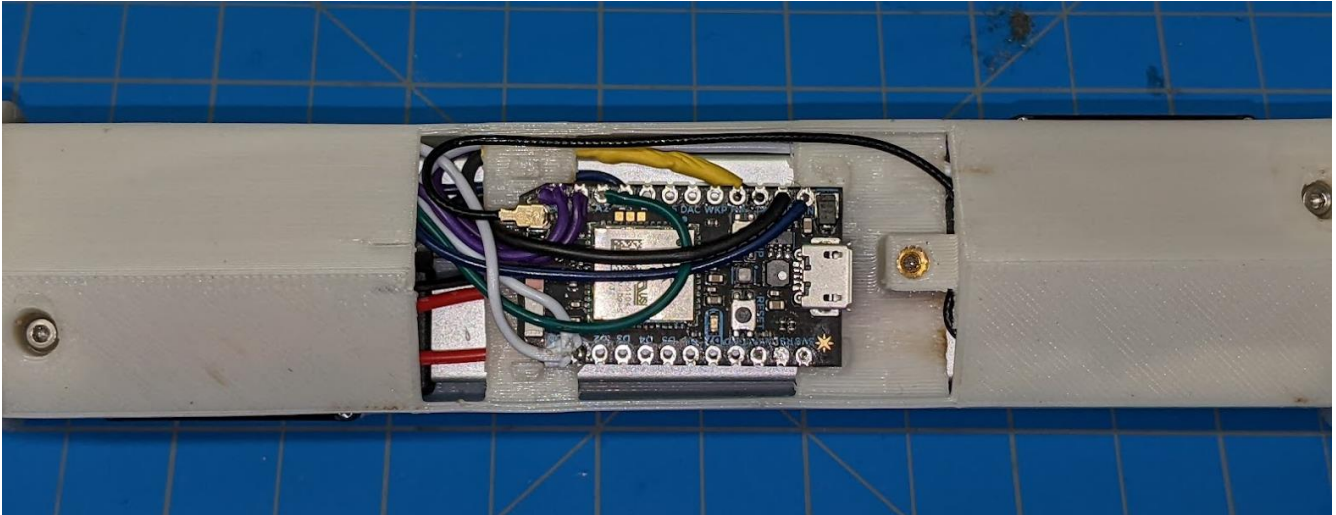


9. Place the bushing into the mount hold of the actuator. And make sure all of the wires not above or close to the hole, it will cause interference when you close the shells.
10. Close the photon side body shell, make sure the actuator wires (black, red, white, purple) do not interfere with the body. And pull all the rest of the wire (green, blue, 2x white, 2x purple) out of the body shell.



Photon Placement

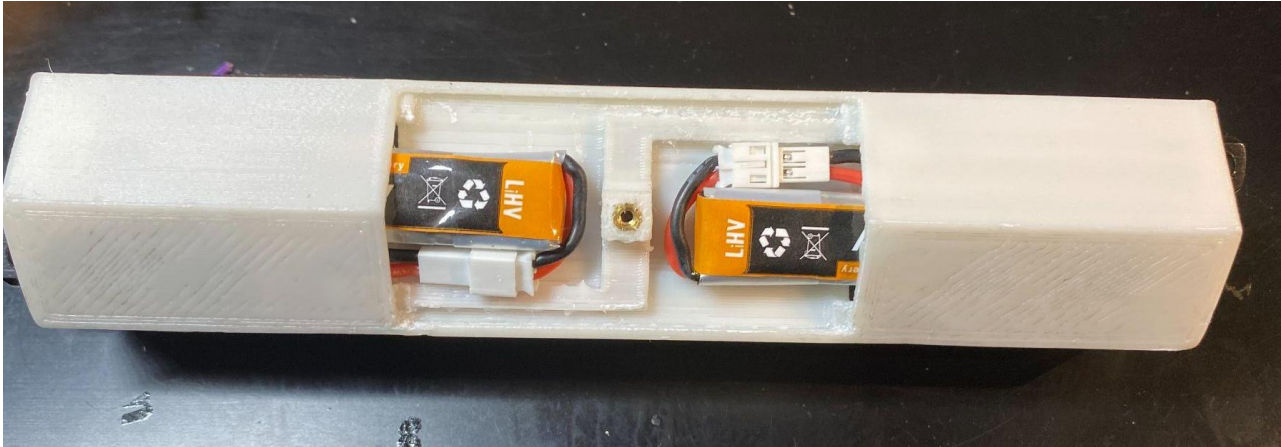
1. Solder the wires to the Photon as per the Circuit Diagram.
 - a. Solder the White and purple wire from SRV0 to the D0 and A0 ports respectively.
 - b. Solder the White and purple wire from SRV1 to the D1 and A1 ports respectively.
 - c. Solder the Blue wire from the Voltage Regulator to the VMN port.
 - d. Solder the Green wire from Voltage Divider to A2 Port.
2. Push all extra wires inside of the body shell.



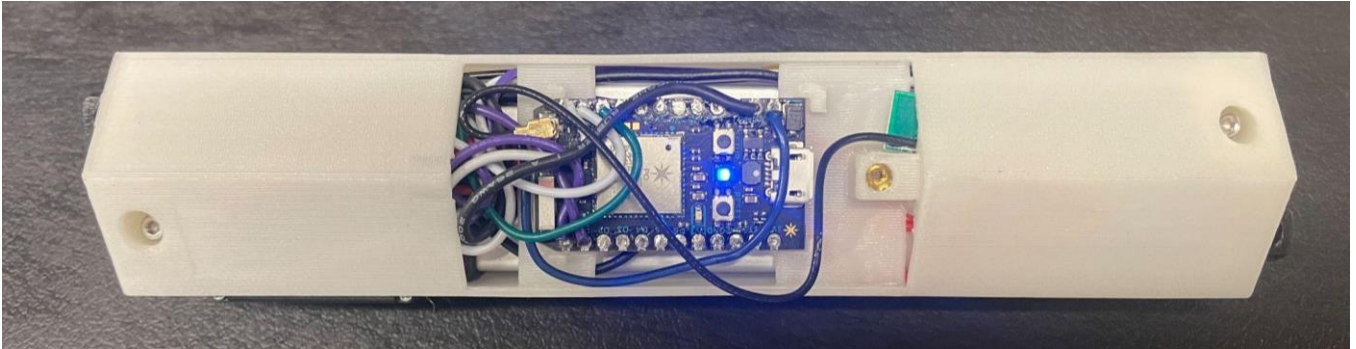
3. Connect WiFi Antenna to the Particle Photon (be careful not to damage the connector) and push it to the inside of the Truss Link body shell.

Body finishing

1. Secure the body shell by using M2X 20 mm stainless steel screw.
2. Place battery like below figure



3. Connector battery to see robot power on. If the indicator light is not on, double check your wires and soldering point. If everything is correct, switch batteries.



4. Secure the inspect window by using M2X8 mm carbon steel screw.

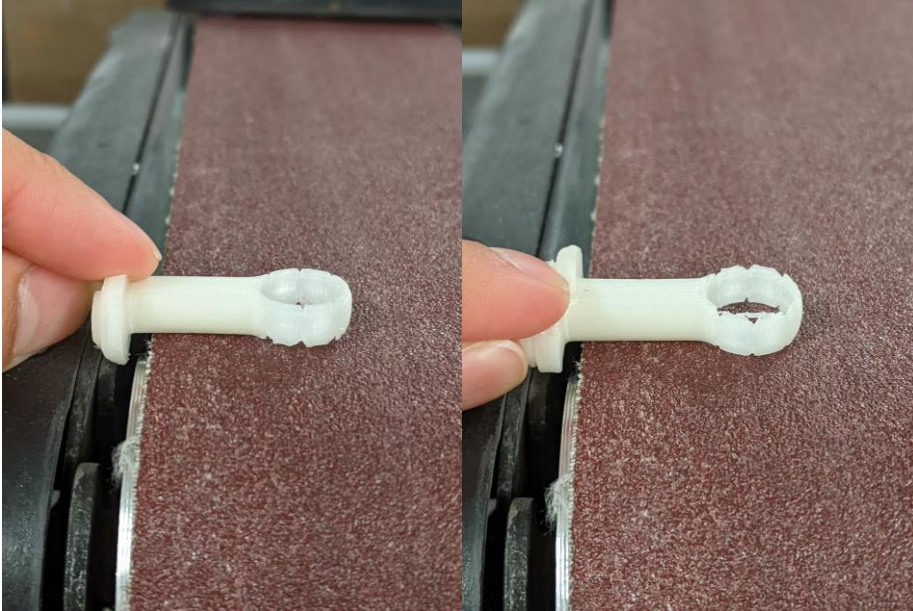


Now, you have a Truss Link body ready, let's assemble connectors!

Truss Link Connector Assembly

Magnet support bar assembly

1. Sand each face of magnet bar to smooth it out and prevent interference:

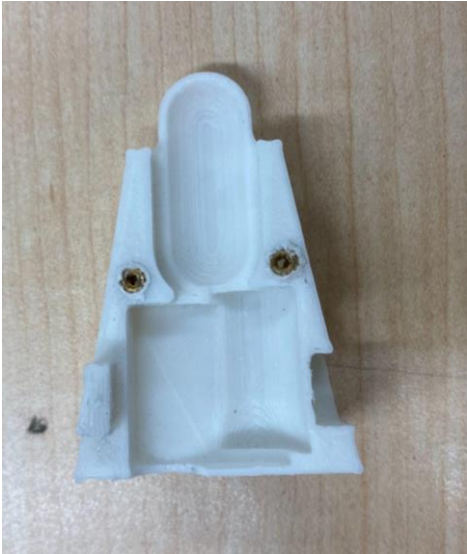


2. Briefly heat round end of magnet holder to soften plastic slightly. Heat it just enough that the plastic doesn't shatter when the magnet is snapped in, not such that it is malleable.
3. Snap magnet into magnet holder.



Connector shell finishing

1. Press heat insert into connector using soldering iron.



2. Drill out connector shell hole with $\frac{3}{8}$ " bit. (not necessary)



Connector assembly

1. Extend each servo 1-2" (this can be done using a script).
2. Remove plastic end caps, taking care not to unscrew the shaft from servo body.
3. Screw the magnet holder into place and center it with the robot body.



4. Apply heat glue on the gap between thread and actuator shaft.
Note: be careful, it's very HOT!



5. Lubricate inside of the connector body.



6. Use graphite to lubricate the magnet ball.
7. Place spring and screw connector together.

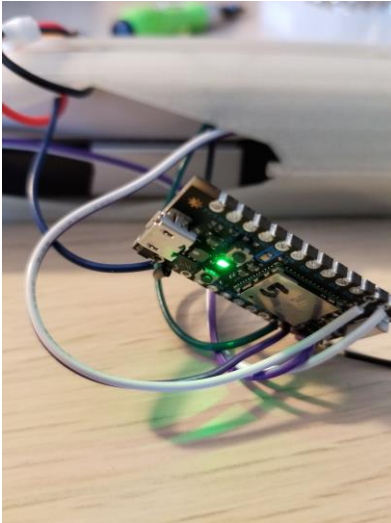


Now, you have a completed Truss Link, Congrats!
Let's connect it to wifi and do some tests!

Testing

Test Wiring and Components

1. Plug in batteries
2. Photon LED should flash



Connect to Wifi

1. Each Photon must be setup to connect to the wifi SSID “team_20-mobile” with password “robots1234” (since the firmware is programmed as such)
2. Follow this setup to connect your photon to the wifi <https://docs.particle.io/quickstart/photon/>
3. Name your photon as an increment of the highest photon id using the format “P#” where “#” represent the number of the photon.

Test Links

1. Navigate to Particle Web IDE: <https://build.particle.io/build/new>
2. On the bottom left-hand ribbon, choose “Devices”
3. Select the number of the Photon you are working with (should be written on the device)
 - a. If not written then select “Add New Device” and set up the Photon as a new device
4. Select the photon “to flash”
5. Navigate to the Code section
6. Select flash the below shared microcontroller code: TestLinks-HardwareTeam.ino
7. On the top left, flash firmware to the Particle
8. Both actuators should extend one at a time



c

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