August 7, 2018

Locomotion Analysis of Worm/Slither Robot

1 Design

1.1 Overview

Using similar controls and actuations to my second wormbot prototype (shown in Fig. 2), a final wormbot could be created to traverse a lattice. The wormbot would use four large servos (HS7950TH) for locomotion and four small servos for gripping, for a total of eight actuators.

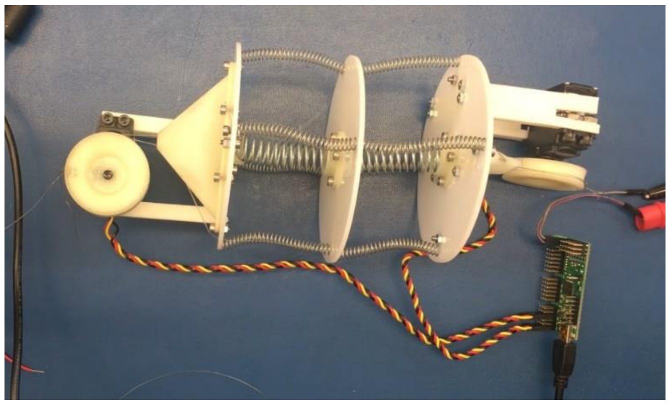


Fig. 1 First wormbot prototype only capable of walking (inchworm) behavior

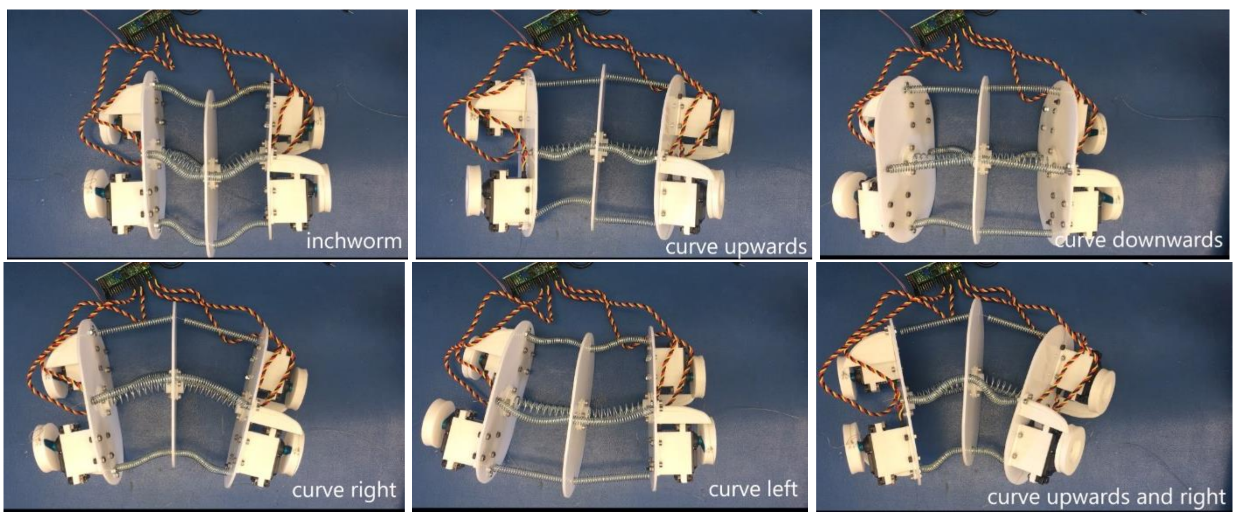


Fig. 2 Several behaviors of my second wormbot prototype

The final wormbot would be constructed from three circular plates, passively connected by springs of length *s* (this simple body is shown in Fig. 3). Four wires would be thread through small holes at the 0, 90, 180, and 270° markers on each plate. Two HS7950TH servos would be attached at each plate. By attaching pulley-like mechanisms to each servo horn, each servo could be converted into a winch.

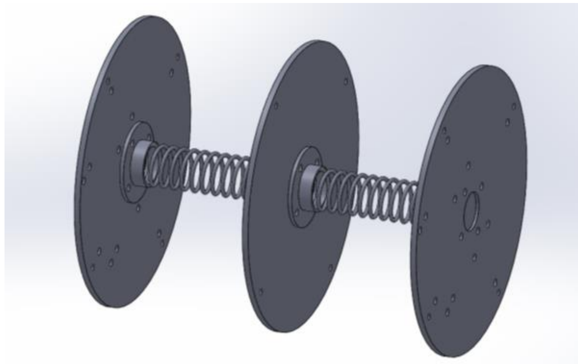


Fig. 3 Basic body of the wormbot (three circular plates connected passively with two springs)

The robot would possess one of four types of gripper feet (each of which use four small servos), depending on the lattice type.

- **DESIGN A:** To traverse face-adjacent (and either vertex-attached or edge-attached) cuboctahedra, the robot could grip onto a single node on each cuboctahedron using a gripper similar to Olivia's spring-activated design.
- **DESIGN B:** The robot could also attach itself to an entire face of a cuboctahedron, resting itself on four of the nodes. This gripper would be similar to Greenfield's voxel transporter design or Ben's new BILL-E foot for cubocatehdra.
- **DESIGN C:** To traverse vertex-adjacent, vertex-attached octahedra, the robot could grip onto a single node (the pyramidal point) of each octahedron using a modified BILL-E style gripper.
- **DESIGN D:** The robot could also attach itself using a foot identical to that of BILL-E, which rests on four nodes of the octahedron.

Each of these grippers require one servo for the actuation of some sort of latching/gripping behavior. In addition, each gripper foot will have a rotating ankle (around z axis) because this will simplify the number of steps required to make in-plane turns.

I considered additionally adding an extra degree of freedom to each gripper foot an almost identical design to BILL-E's twisting ankle. A twisting ankle would allow for simpler concave turns as shown in Fig. 4. However, this concave-turn key state does not allow enough clearance for an end effector or voxel transport payload on the front of the robot. In addition, the twisting ankle reduces the stability of the overall design because of its tenuous connection with the robot base.

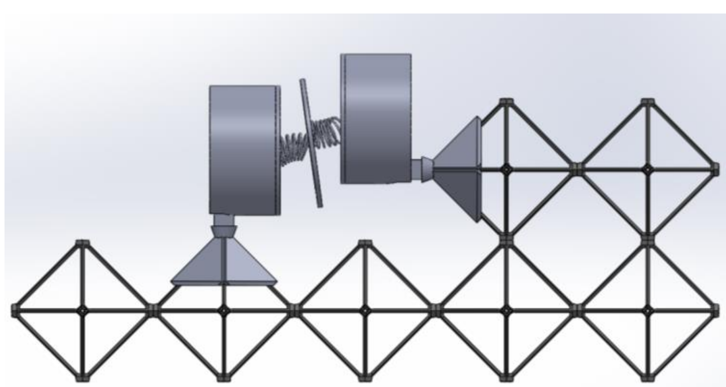


Fig. 4 Wormbot design with BILL-E gripper feet executing a concave turn

A final note: we can already see an advantage of designs B and D over A and C; the single-node grippers used in A and C are less precise because they have less alignment features.

1.2 End Effector and Voxel Payload Integration

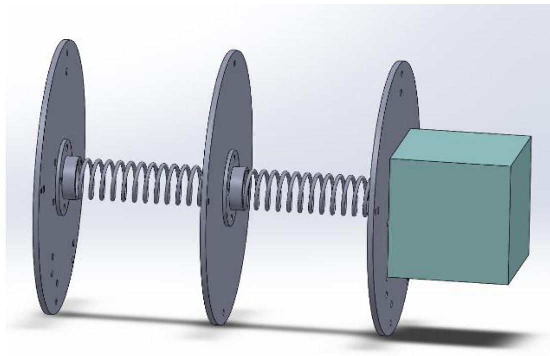


Fig. 5 Black box model of end effector/voxel payload integration

The only viable way to include an end effector or voxel transporting payload into wormbot is to attach it to the front or back of the robot. An attachment to the top of wormbot would compromise the range of curvature and lead to instability.

Because wormbot's gripper feet always stay colinear with their attached circular plates, an attached payload should not interfere with the lattice in any destructive ways. The only place where interference could become relevant is during a concave turn maneuver, where the robot may not be able to approach the concave corner due to the protruding payload.

A possible solution could be to use the rotating ankle to reorient the robot, when a situation like this occurs, so it can approach the concave turn with the end effector/voxel transport attachment on the back. However, this would not be a viable solution for a robot with *both* an attached end effector and voxel transport payload.

2.3 Robot Size

Using servos with 360° continuous rotation, wormbot could theoretically have a minimum plate diameter of 2.75in, independent of the scale of the lattice, and could navigate voxels with a minimum pitch of 3in.

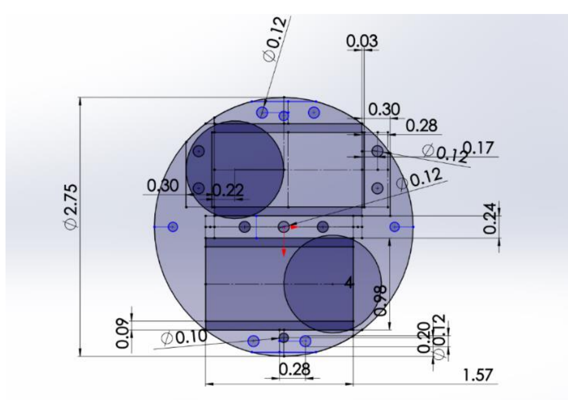


Fig. 6 How I arrived at the calculated minimum plate diameter (2.75in)

However, it is important to consider the volume of the servos attached to the two exterior circular plates. These regions should extend a distance

$$C = h_{servo} + h_{pulley} + b.$$

From my prototype, $h_{servo} = 1.50in$, $h_{pulley} = 0.4in$, and $b = 0.5in$ (a buffer so the pulleys do not interact) so the final robot should have $C = 2.40in$. The servos could only fit on a robot traversing 3in pitch lattice if they were exactly centered around the gripper feet. This would mean the springs would have to be able to reach a maximum compressive distance of

$$s_{min} = \frac{x - C - 3w_{wall}}{2}$$

where *x* is the lattice pitch and w_{wall} is the thickness of each circular plate (I have been using 3/32in). For a lattice with 3in pitch, s_{min} is 0.3188in.

To fully validate that a robot of these dimensions could exist on a 3in pitch lattice, I must also calculate the maximum extension of the spring s_{max} to determine if a realistic spring exists that can compress from s_{max} to s_{min}. the maximum extension of the spring can be estimated using *L*, the maximum length the fishing line must extend for wormbot to achieve all of its key states. A crude approximation of *L* can be derived from the fifth key state of wormbot (which is proposed in 2.1), where the robot experiences the maximum extension.

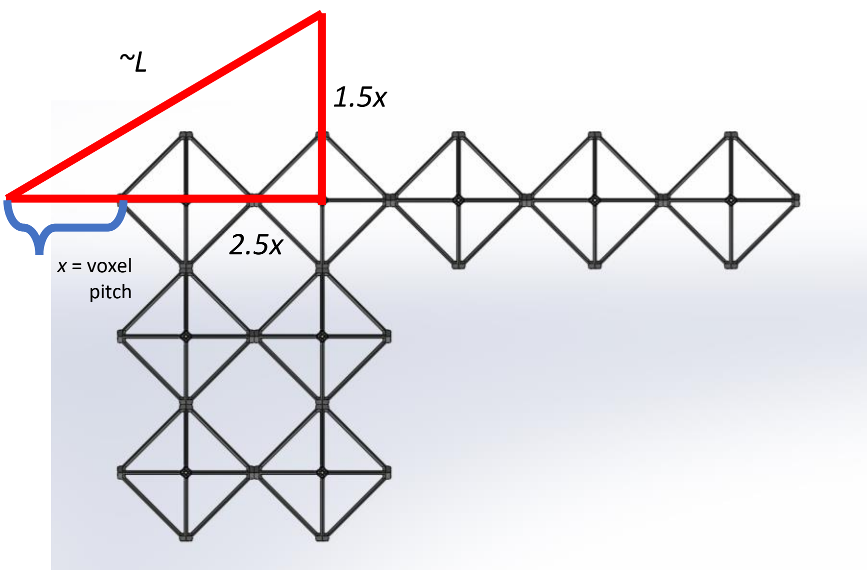


Fig. 7 Estimation of L using key state five configuration

$$L \approx \sqrt{(2.5x)^2 + (1.5x)^2} = \sqrt{8.5}x$$

Using *L,* we can calculate s_{max}:

$$s_{max} = \frac{L - C - 3w_{wall}}{2} = \frac{\sqrt{8.5}x - C - 3w_{wall}}{2}$$

For a 3in pitch lattice, s_{max} is 6.0652in. No compression spring exists on McMaster that could meet these requirements. This hypothetical spring would need to compress to 5.25% of its original length, which would not be feasibly manufacturable for this application.

Based loosely on springs from the McMaster catalog, I estimate 30% compression is around the maximum possible compression that can be realistically achieved. Using this requirement, we can estimate the minimum voxel pitch wormbot could operate on.

$$\frac{s_{min}}{s_{max}} = \frac{x - C - 3w_{wall}}{\sqrt{8.5}x - C - 3w_{wall}} \geq 0.3$$

Using the aforementioned values of C and w_{wall}, I conclude that, while the minimum circular plate diameter of wormbot is still 2.75in, the minimum possible lattice pitch wormbot could operate on is approximately 15in ($x_{min} \approx 15in$). This pitch is already larger than that of the Yosemite voxels. At this scale, questions about the torque limitations of the servos begin to arise. Will two small HS7950TH servos be powerful enough to lift the weight of two additional servos along with other robot hardware at the end of beam of length $L \approx \sqrt{8.5}x \approx \sqrt{8.5}(15in) \approx 44in$? From a quick back-of-the envelope calculation, I estimate the torque applied to be around 30kg.cm. A HS7950TH servo (at its max voltage of 7.4V) has a stall torque of 35kg.cm. So, this could be possible.

Without continuous servos, wormbot's minimum plate diameter would scales linearly (from 2.75in) with the size of the voxels according to the following equation:

$$d_{min} = w_{servo} + 2w_{wall} + 2d_{screw} + 2r_{pulley}$$

$$\pi r_{pulley} = 2L - 3 = 2\sqrt{8.5}x - 3$$

$$d_{min} = w_{servo} + 2w_{wall} + 2d_{screw} + \frac{2(2\sqrt{8.5}x - 3)}{\pi}$$

Using the dimensions from my prototypes:

$$d_{min} = 0.79in + 2(\frac{3}{32}in) + 2(3mm) + \frac{2(2\sqrt{8.5}x - 3)}{\pi}$$

$$d_{min} = 11.6619x - 0.6961in \quad , \quad \text{for } d_{min} > 2.75\text{in}$$

2 Locomotion Steps

2.1 Key States

1. **One-voxel-wide compression**

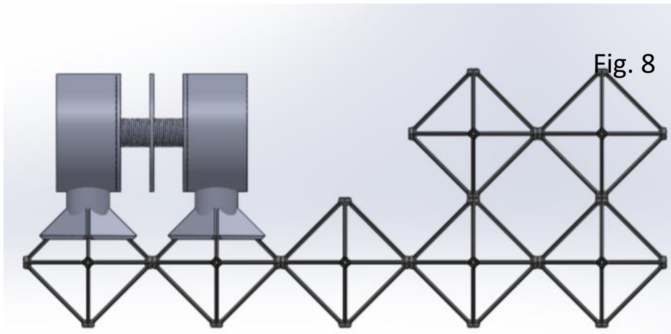


Fig. 8

Immediately, this key state requirement eliminates two of the four possible designs of the wormbot. Designs B and D are eliminated due to interference between the robot's gripper feet. During the 1-voxel-wide compression step, both feet are trying to rest on a shared node, an impossible configuration given the gripper foot design. This leaves A and C; however, these designs lack the helpful alignment features of the more robust gripper feet from B and D.

2. **Two-voxel-wide expansion**

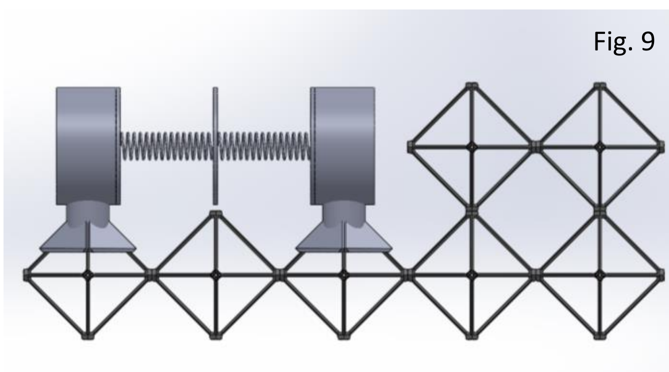


Fig. 9

3. **+1 step**

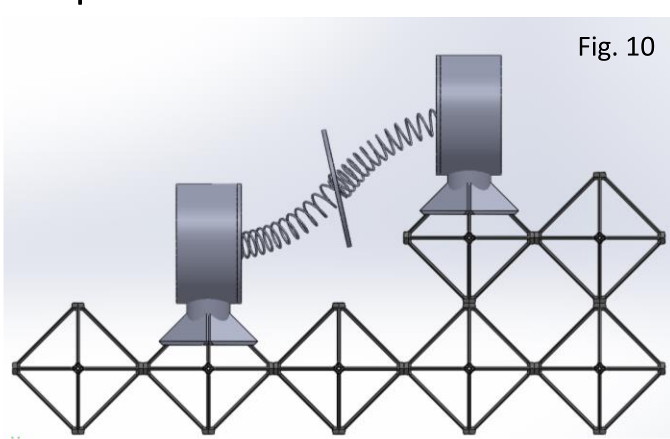
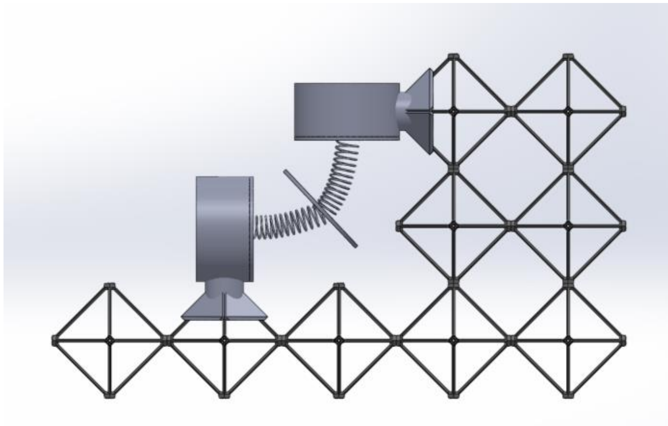


Fig. 10

4. **Concave step**

Fig. 11



With this configuration, there is a high likelihood of interference between the robot and the voxels since the springs are likely to distort/bulge due to the sharp curvature.

5. **Expanded convex step**

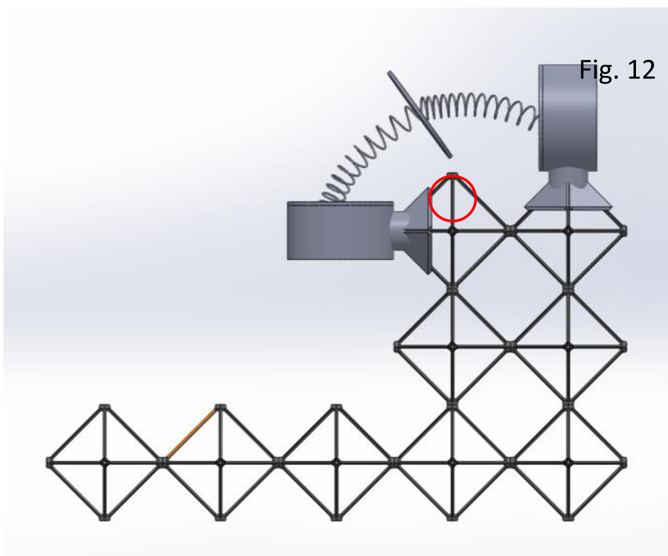


Fig. 12

Again, interference is a valid concern with state five (see the circled region).

To analyze the viability of designs A and C, I will analyze the dynamics of the transitions between these five key states through an analysis of the five functional locomotion requirements of the robot: walking, making in-plane turns, stepping up/down, making concave turns, and making convex turns.

2.2 Walking

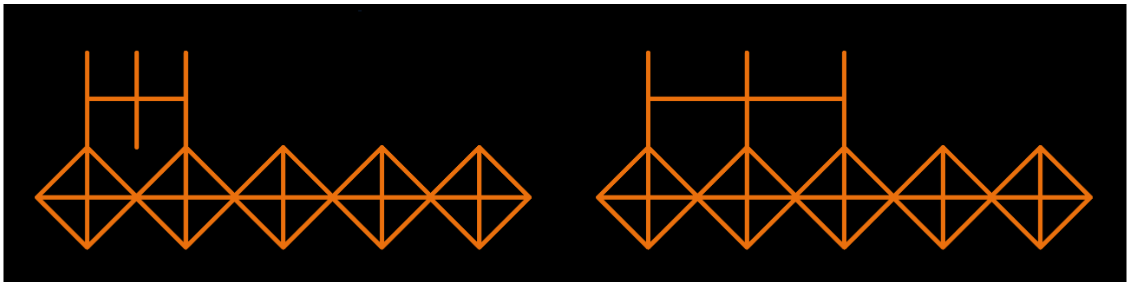


Fig. 13 2D locomotion steps of walking

Key states pattern: 1, 2

To linearly traverse a lattice, the robot must alternate between key states 1 and 2. To achieve these states, the robot must actuate all four of its main servos simultaneously. However, slight errors in the concurrency of the winding of the servos and the alignment of the circular plates are likely during this motion. Additionally, since neither key state represents the fully expanded state of the robot, the springs that propel the walking motion will always possess some potential energy (because they are in compression).

The combination of these factors causes wormbot to twist and distort while transitioning between states 1 and 2. This behavior can be seen in Fig. 14 in my second prototype of wormbot.

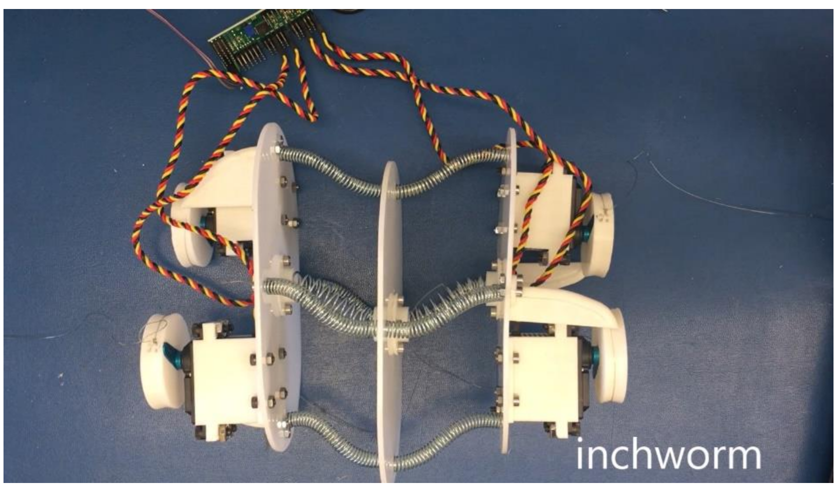


Fig. 14 Distortment of springs during compression in second wormbot prototype

This distortment has the potential to cause interference between wormbot and the lattice it is traversing. Due to this behavior, we can eliminate robot A (which is designed to traverse a vertex-attached or edge-attached face-adjacent cuboctahedral lattice). When attached, the outer surface of the cuboctahedra is bounded by horizontal planes, as seen in Fig. 15 (unlike the vertex-adjacent octahedra which have a jagged outer surface). Any distorment of the wormbot inevitably will interfere with the cuboctahedra because of their planar faces, eliminating design

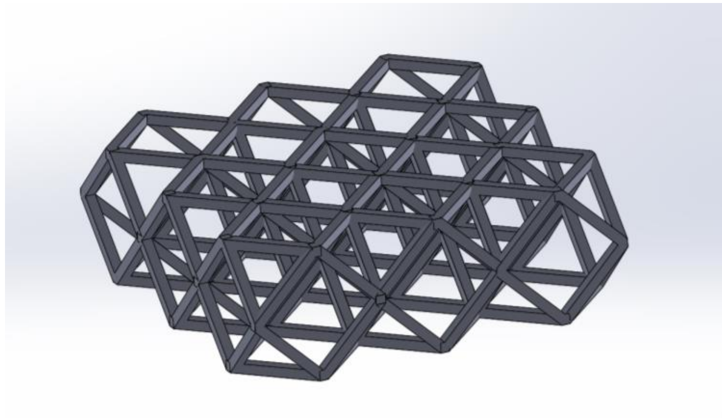


Fig. 15 Face-adjacent cuboctahedral lattice

2.3 In-Plane Turn

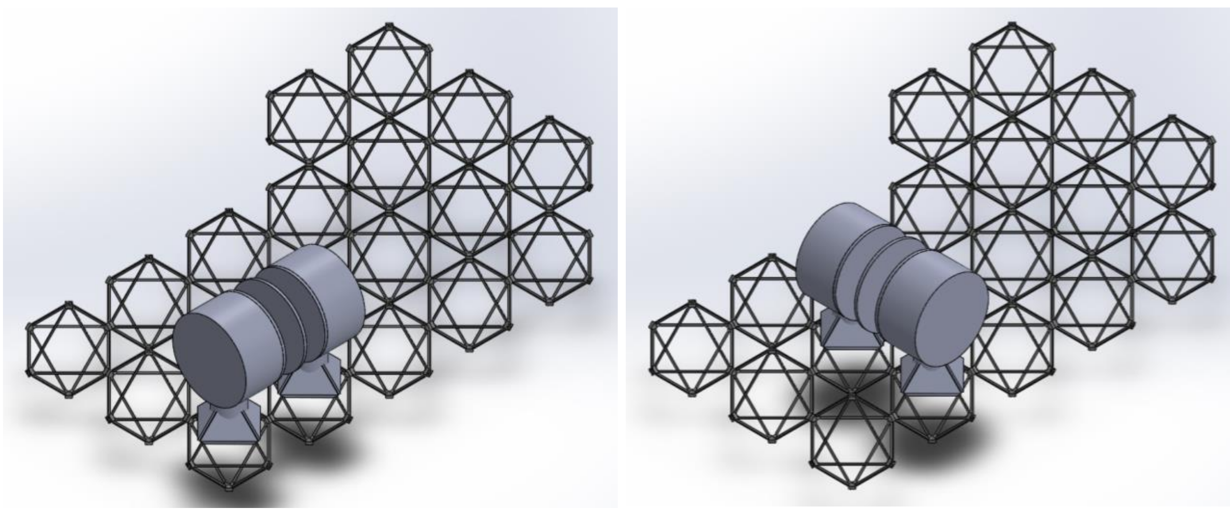


Fig. 16 3D locomotion steps of an in-plane turn

Key states pattern: 1,1

To make an in-plane turn, wormbot will use the rotating ankle of one of its gripper feet. Before it rotates, however, it will have to slightly curve upwards for clearance with the lattice. Distortment and twisting could come into play during this curvature and could lead to interference with the lattice.

2.4 Stepping Up/Down

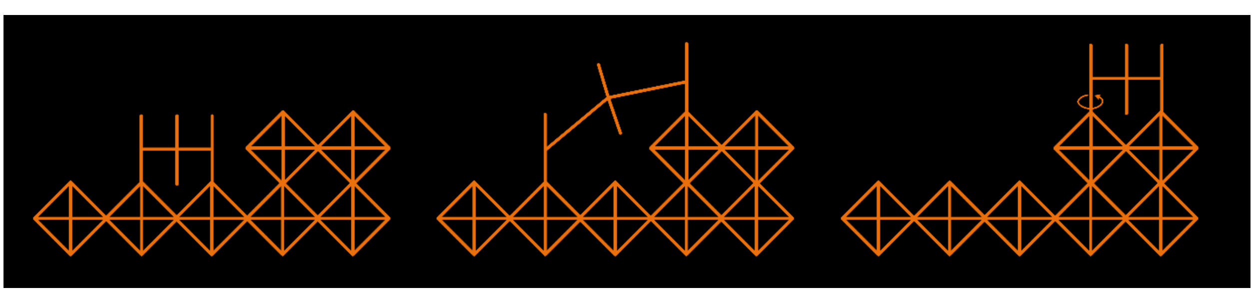


Fig. 17 2D locomotion steps of stepping up/down

Key states pattern: 1,3,1

To initially transition between states 1 and 3, wormbot move curve upwards and expand. It must avoid interference simultaneously between its gripper foot and the lattice, and its body and the lattice. Once it achieves key state 3, it can use its rotating ankle to return to a one-voxel-wide, planar, compressed position.

2.5 Concave Turn

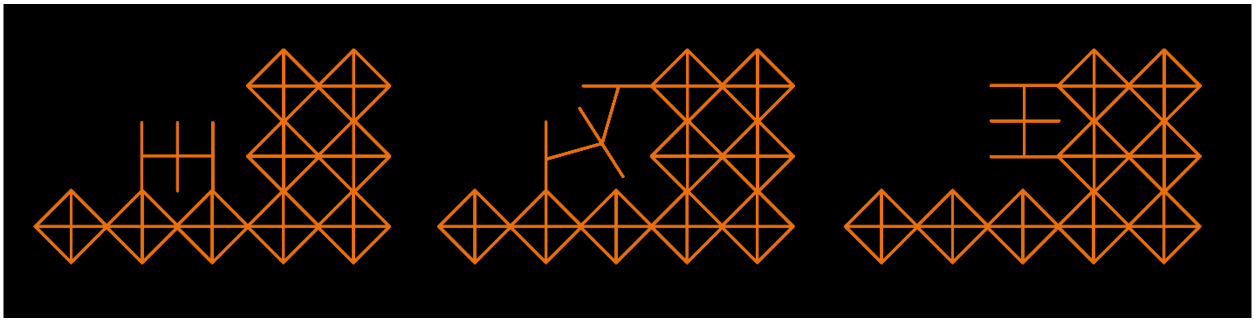


Fig. 18 2D locomotion steps of a concave turn

Key states pattern: 1,4,1

Interference between the robot and the lattice is still possible during the concave turn, although less likely than some of the other key states because there is more clearance with each step.

2.6 Convex Turn

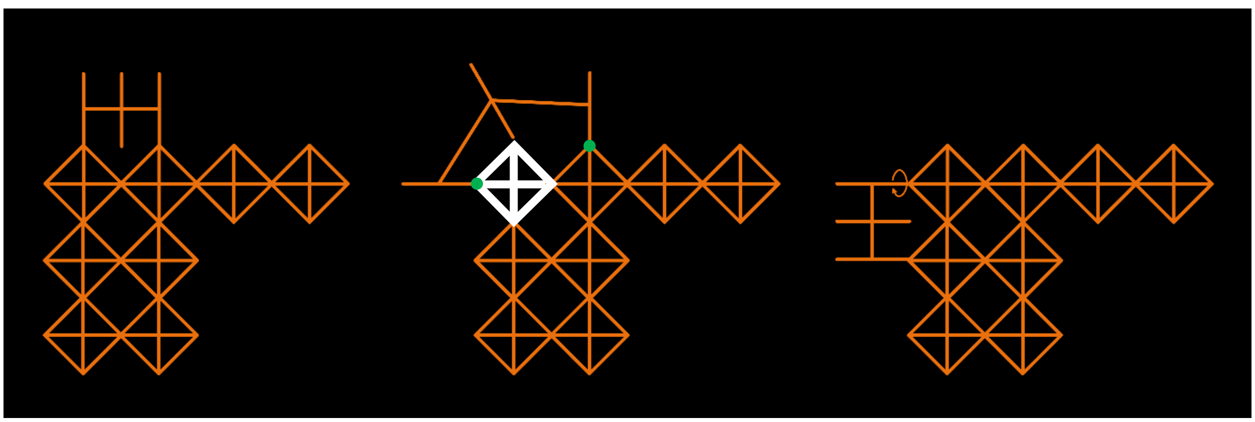


Fig. 19 2D locomotion steps of a convex turn

Key states pattern: 1,5,1

The convex turn, particularly the configuration of key state five during the convex turn, seems to the most problemtaic, and likely impossible, maneuver of all steps of wormbot's locomotion.

The main question, shown in Fig. 19: can wormbot physically bend into a position where it is attached at the green nodes, but does not interfere with the white voxel?

To prove the validity of this motion, many factors must be considered:

- The stiffness of the springs used
- The effect of gravity, which will cause additional compression and bending in the springs
- The possible distortion and twisting of the springs due to misalignment or lack of concurrency in the actuation

Given the scope of this study, I did not do the calculations necessary to determine the viability of this maneuver. However, given the many variables affecting wormbot's behavior in this situation, I hypothesize that this motion is impossible.

Given the other challenges of wormbot's design plus the shear complexity that would need to be put into its path planning, I propose it is definitively not a valid type of locomotion for cuboctahedra and likely not a valid type of locomotion for octahedra.

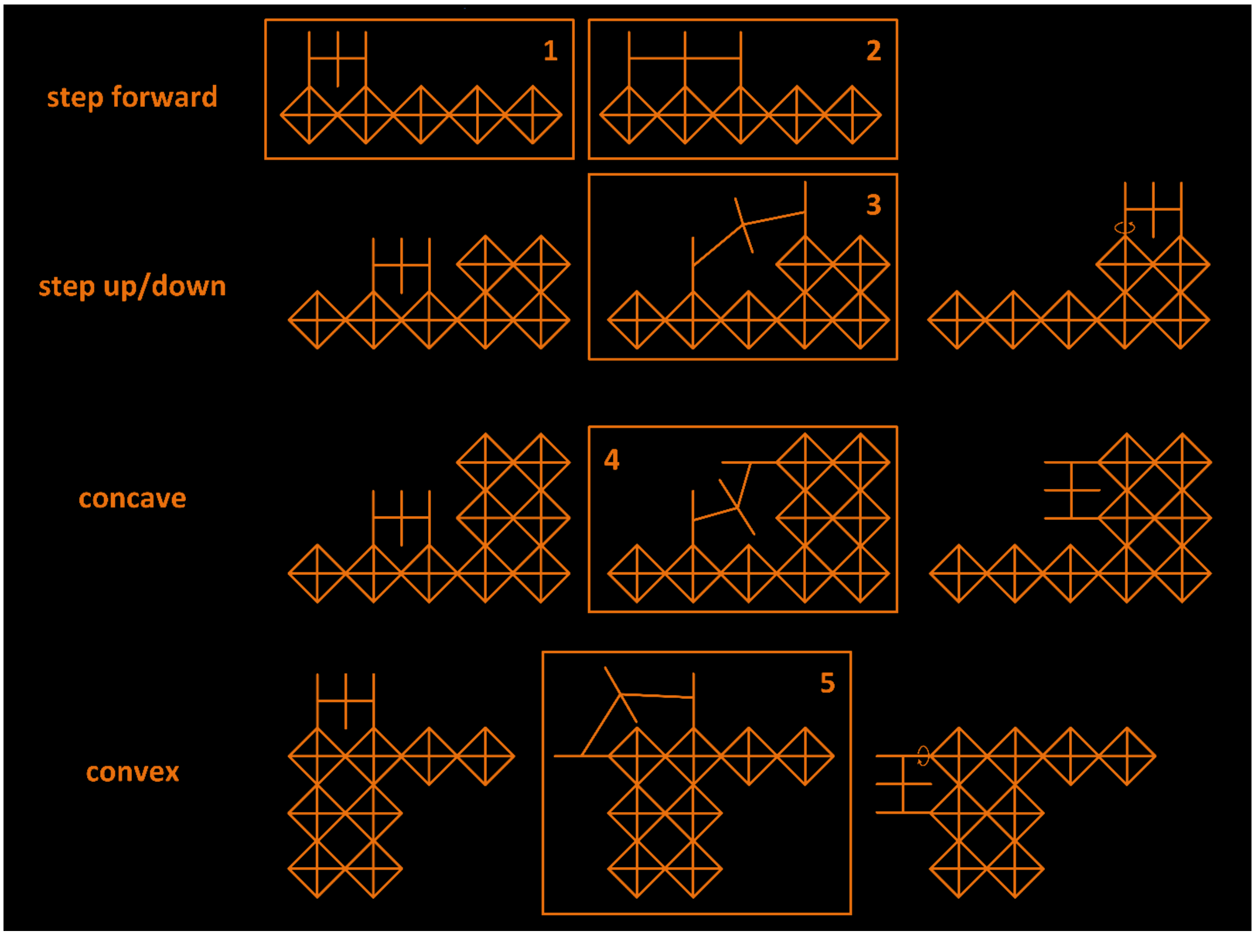


Fig. 20 Two-dimensional overview of the dynamics of four of the five key locomotion requirements of wormbot with unique key states highlighted