Reimagining the Strandbeest as a Compliant Mechanism

By Conor Bergin

I am designing a singley actuated walking robot. The robot should be powered by a single motor and should walk at a constant speed in a straight line.

How do you turn a rotational motion into a linear one?

The obvious answer is a wheel. If you need to walk, however, you need a linkage which will transform the circular motion into a sort of semi-circle; the foot must lift off the ground, reach foward and then pull back. By dividing the robot into independant legs and driving them with a crankshaft, only one planar linkage needs to be designed. This is how the Jansen and Klann mechanisms work.

Compliance

To further complicate things, I decided that it would be a good idea to make the linkage out of a single piece of material, instead of rigid joints it would have flexible ones. The advantage of being made from a single piece of material is it can be made in one operation, and as it it is a planar mechanism, it can be made in any thickness and any size, only the x and y geometry needs to be consistent. Using 3D printing, I can test and improve my linkages very quickly.

How do you design a compliant mechanism?

Compliant mechanisms are much more difficult to model than rigid body mechanisms. There are several approaches, the most obvious being the Finite Element Method with a 3D mesh of the part. This is accurate, but computationally expensive. We can simplify the problem by turning our mechanism into a system of 1D beams with rigid connections, allowing us to use Euler-Bernoulli beam equation:

$$M = EI\frac{d\theta}{ds}$$

Normally we would replace the curvature with the 2nd derivative of y in terms of x:

$$M = EI\frac{d^2y}{dx^2}$$

This substitution is only valid for small deflections because the length of the beam isn't constant, so we have to use the original equation. Unfortunately the ODE problem that arises once we define our boundary conditions is still complex. It's faster than FEM, but its still too slow.

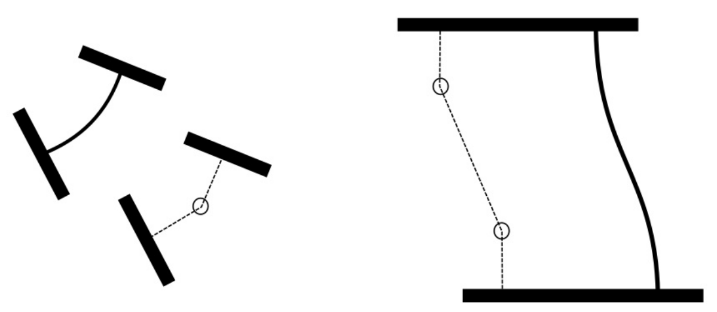

Figure 1. - PRBMs of a simple flexure and a parallel linkage

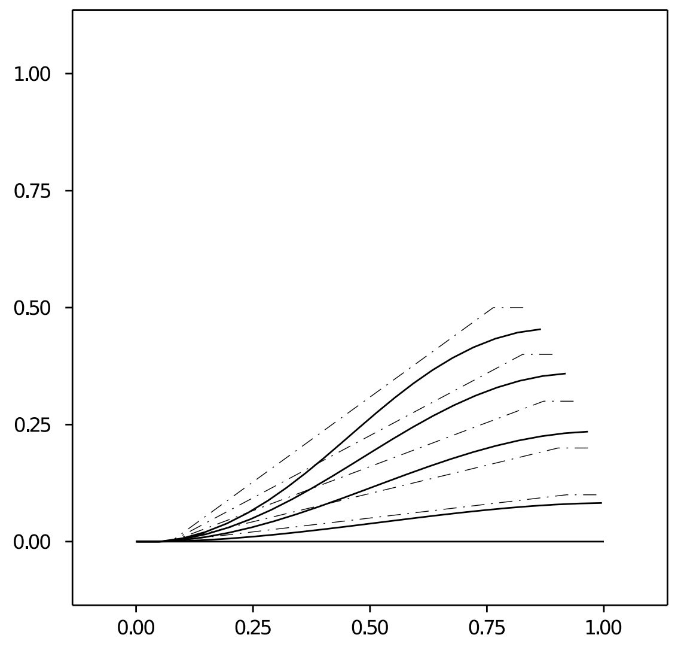

Figure 3. - PRBM vs ODE

Using the Psuedo Rigid-Body Model

A less accurate, but far simpler method is creating a Pseudo Rigid-Body Model and solving that. A PRBM is kinematically similar rigid-body model with torsional springs at the joints to model the elasticity of the material.

I will use two distinct PRBMs, a simple joint to represent a small flexure, and a three link mechanism that represents a compliant parallel linkage. In Figure 3. I compare the PRBM to the ODE solutions at different displacements. The paths are very close despite the large deflection, and considering the how much it simplifies the problem this is an excellent trade-off.

Figure 2. - A Strandbeest [1]

We can now design the mechanism as if it were a rigid body model, with a few limitations:

1. Deflections should be minimised, the PRBM becomes increasingly inaccurate, and the real part might break due to too much strain.

2. Only two bodys can use a pivot, because in reality that pivot is in the middle of a beam.

Because this is a difficult problem I wanted to use an existing mechanism as a starting point. I hade two choices, the Jansen Mechanism and the Klann Mechanism, both popular planar walking linkages.

I decided to use the Jansen mechanism, used in Theo Jansen's Strandbeests, as a starting point for my own linkage because the deflections at the joints were smaller, meaning I would have to do less work to turn it into a compliant mechanism.

Firstly I separated all the joints that would overlap in a compliant mechanism. This only affected two joints.

Secondy I adjusted the legths of the members until I had satisfactorily small deflections at all the joints.

After changing the geometry the path of the foot had been significantly affected. So I generated the paths for 100 different configurations of the foot dimensions, the plots for these can be seen in Figure 6. It looked like the optimal path was between the two paths seen in Figure 7, so I interpolated between them to get the final path seen in Figure 8. Though completely functional, it is worse than the original path, but considering how many parameters there are in the model, and that I was only changing 2 at a time, this was expected.

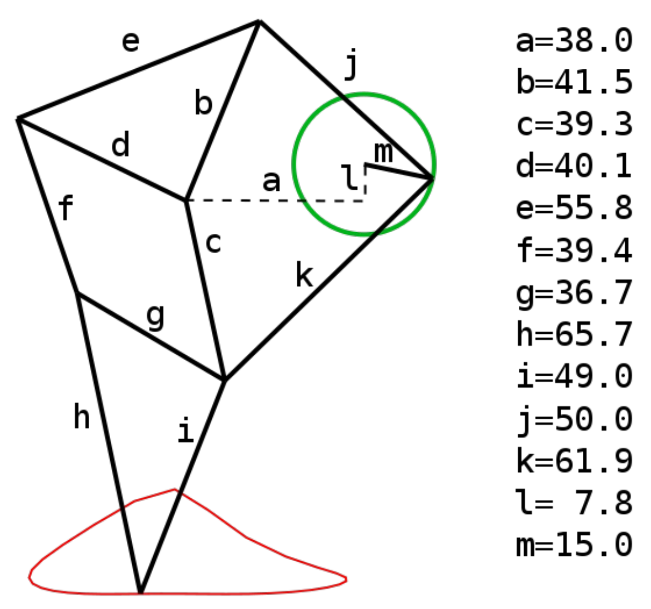

Figure 4. - Jansen Mechanism [2]

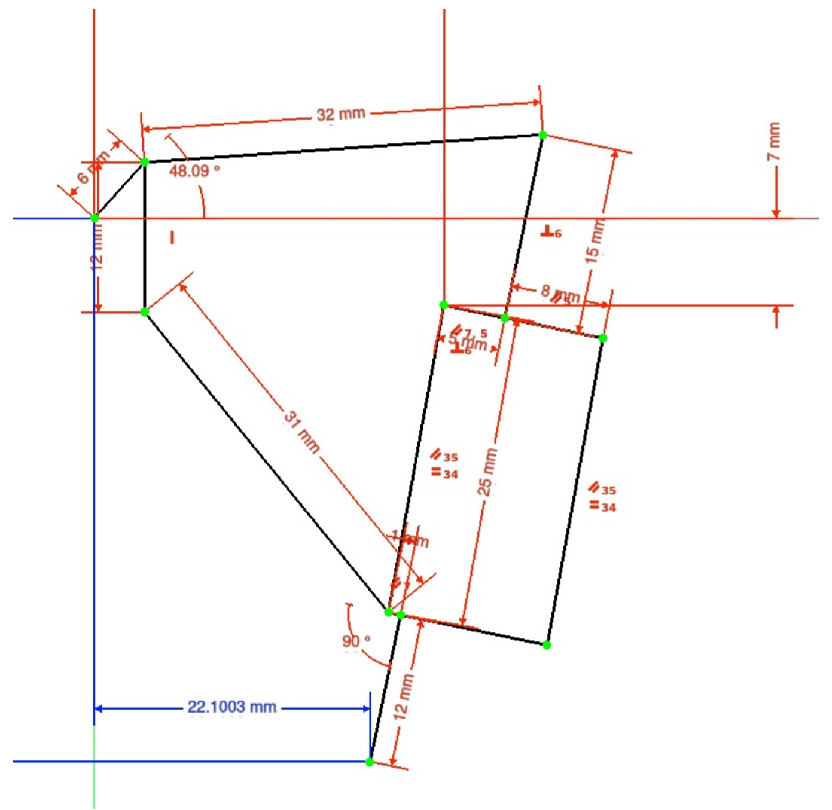

Figure 5. - My Mechanism

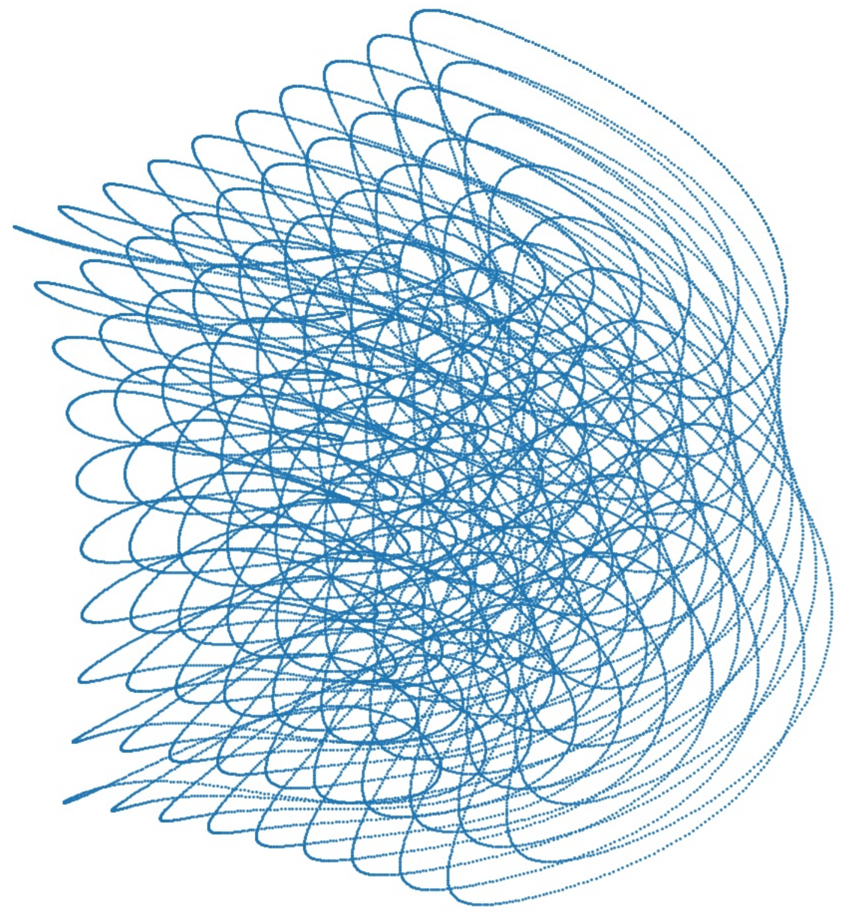

Figure 6. - Paths created by different leg geometries

Figure 7. - A subplot of Fig. 5

Figure 8. - Optomised Path

I could then draw a compliant mechanism using my PRBM in CAD and do an FEM analysis to verify my design. I worked backwards from the rules I used to make the PRBM, I replaced the parallel rigid mechanism with the kinematically equivalent parallel compliant mechanism, replaced the 3 remaining joints with compliant hinges, and then filled in the gaps with volumes large enough to not influence the overall deflection. I then generated a mesh and ran the solver for 12 different displacements, of which 6 can be seen opposite, next to the equivalent PRBM. I recorded the displacement at the foot and plotted it so I could compare it with the path of the PRBM. As can be seen in Figure 9. the FEM path has lost some of properties, it doesn't lift as high off the ground and the contact part of the cycle is less flat.

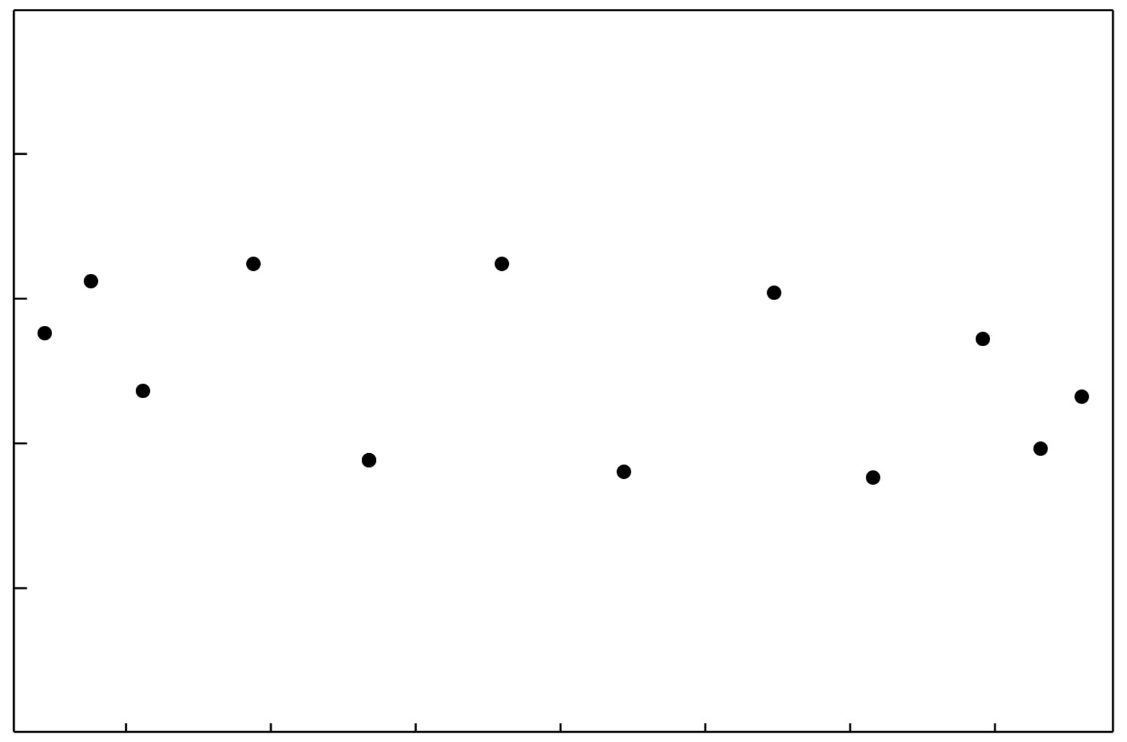

Figure 9. - FEM Path

Further work:

Find a way to optomise the PRBM properly, at the moment it is too time consuming to change more than two parameters at one time.

Use an ODE solver to solve the mechanism as a system of large displacement beams.

There might be potential to topologically optimize the mesh to the exact displacements required, skipping all of the prerequisite steps.

Dynamically analyze the mechanism so the motor wastes less torque overcoming the internal forces.

References
[1] Image: https://www.flickr.com/photos/bridell/3236492322/in/photolist-5VZSpL-askPJE-JJhew7-5VZSb7-JJhdL9-5VVwGc-5VVwmp-5VZSgq-5VZS1d-5VVwAz-ee4dWU-5VZRWJ-ceLa7U-FsvLSw-edXsYR-JJhdCy-JJhe1N-cMyaG9-dmo1Gt-LHEK4n-9hpAk5-ceL9Ry-EgC9EF-mNx8pB-oFd8uM-meeh6g-ooYYMh-oFg98N-aNrbTn-oFg9KE-fHCXgV-5VZRSU-L6LU1P-6BHB2S-oHezt8-9hmvFz-bvJqBx-oHeyqg-9hmpWM-qds9ds-9hmqEt-mNyV75-26N8cQb-NjaUK8-py1wWC-aNrb7g-9hpw31-3A2gJn-9hpvty-bvJojp
[2] Image from https://commons.wikimedia.org/wiki/File:Strandbeest_Leg_Proportions.svg