Four-Legged Theo Jansen "Strandbeest" Walking Mechanism

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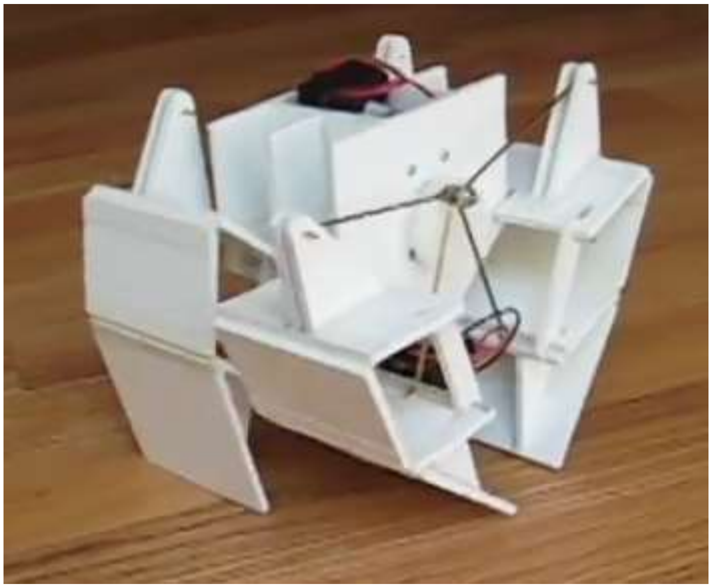
Note: This is a PDF version of the web page: http://scottburns.us/walking-mechanism/

Theo Jansen is known for his "Strandbeest" walking mechanisms made of plastic tubes that are powered by the wind and roam the shores of The Netherlands. Many people have created variations on his design using the eight-bar mechanism that forms each leg. Usually, there are a large number of parallel legs needed to keep the walking device stable.

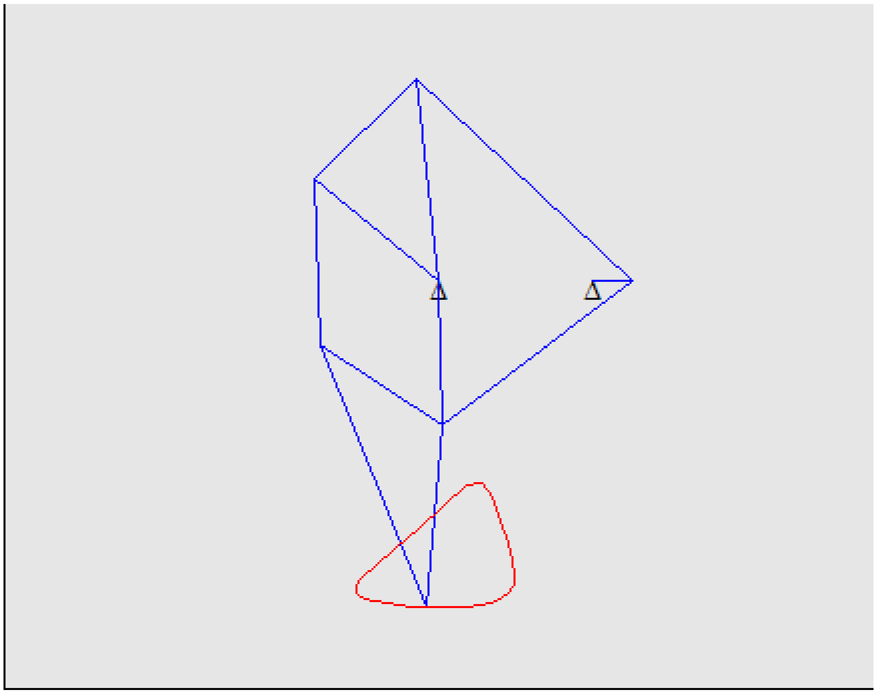


I have developed a version that only needs four legs. I used a mathematical optimization technique to design the legs to make this possible. Here is a YouTube video of the device in action:

https://youtu.be/1MhvUW54fcM

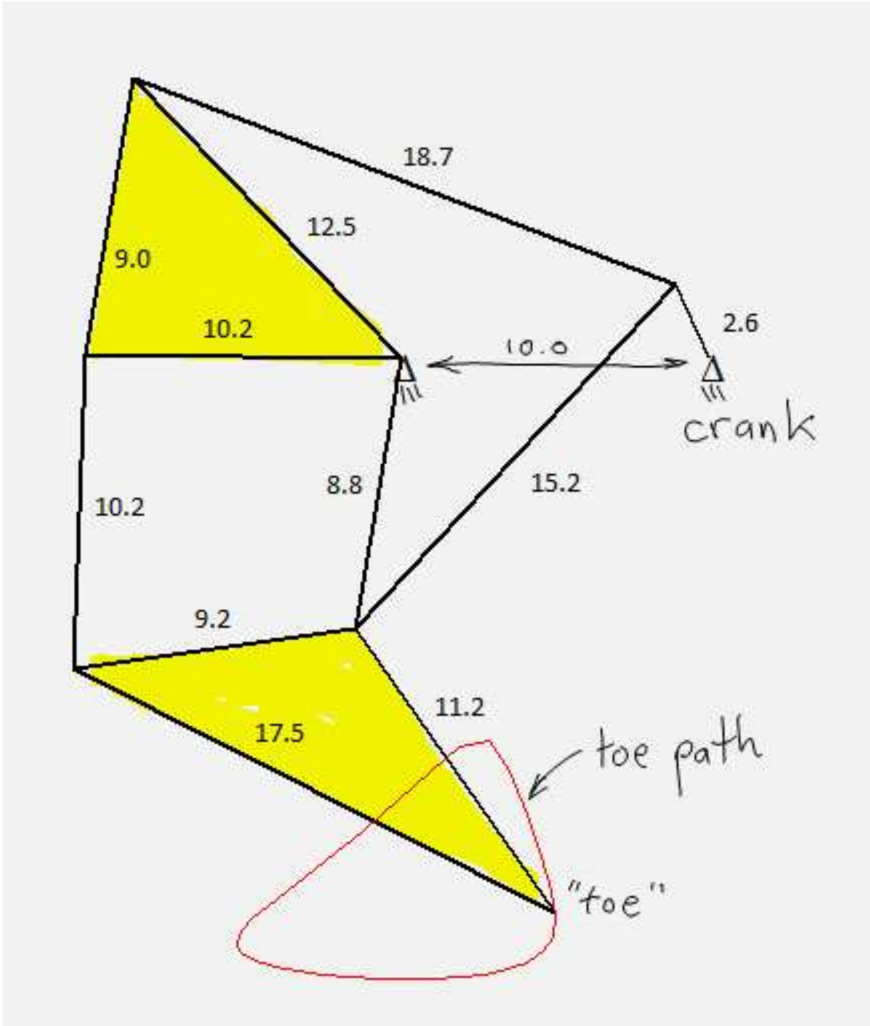
Design

Here is an animated GIF of the starting design. It was a trial and error process to find a mechanism that behaved roughly as a walking mechanism.



The starting design for the 8-bar leg mechanism. (Click image link to animate.)

This mechanism is uniquely defined by the 11 line segment lengths and the distance between the two supports:

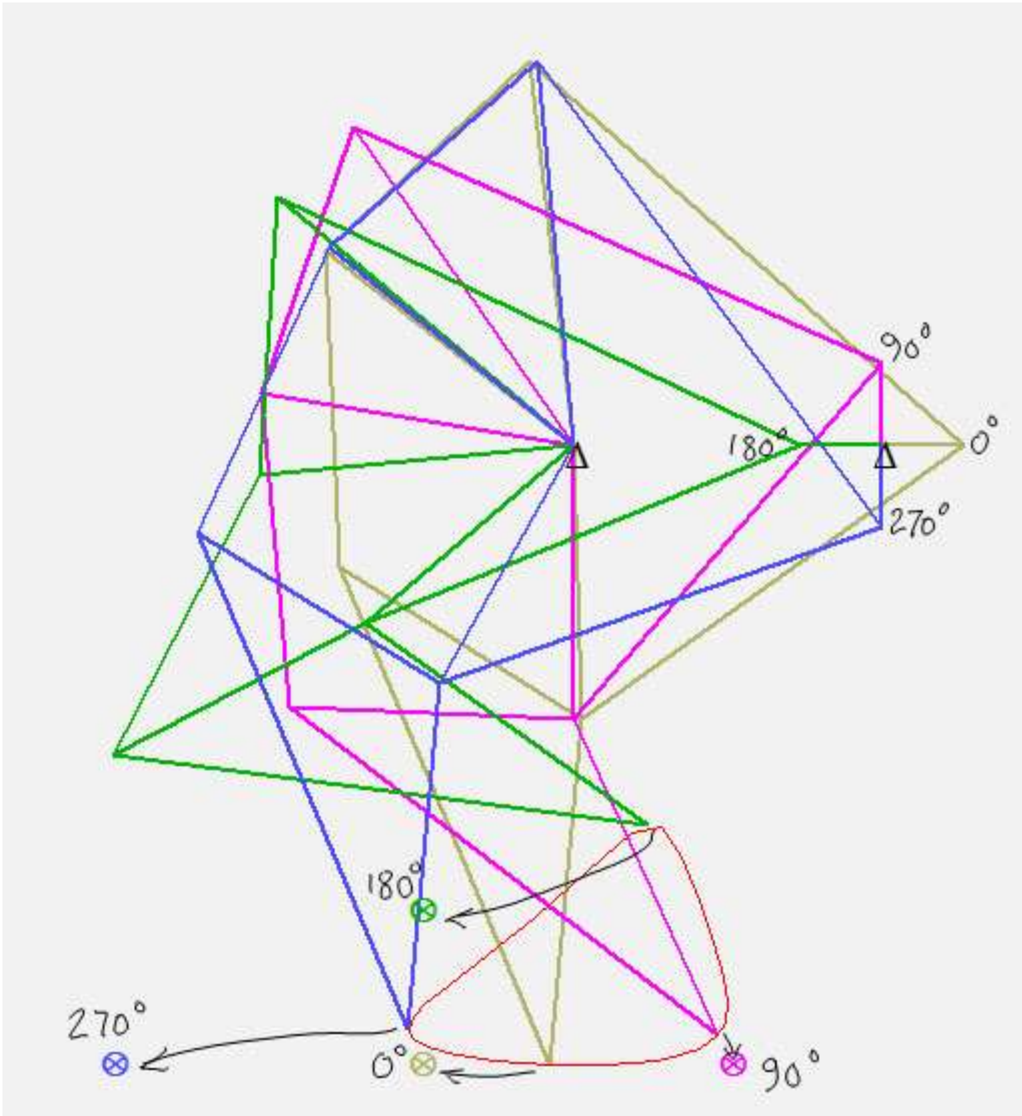


This mechanism belongs to the “8-bar mechanism” category because it contains 8 rigid bodies (5 line elements, two triangles, and the ground element). One of the links is designated the “crank” and its motion is controlled by a motor. A “toe” point is defined on one of the elements and it traces out a “toe path” as the crank makes a full revolution.

My goal was to adjust the lengths of the 11 line segments so that the toe path had a desired shape, specifically, a flat portion on the bottom that accounted for at least one half of the crank rotation, and the remaining portion sweeping above the flat portion. This type of toe path will produce a good walking gait.

To achieve the desired toe path, I employed mathematical optimization, sometimes called nonlinear programming. The optimization statement comprises an objective function and a set of constraints. Both the objective and the constraints are functions of the design variables, which are the 11 line segment lengths in this case.

To formulate the objective function, I defined four “precision points,” depicted by the ⊗ symbol in the following figure:

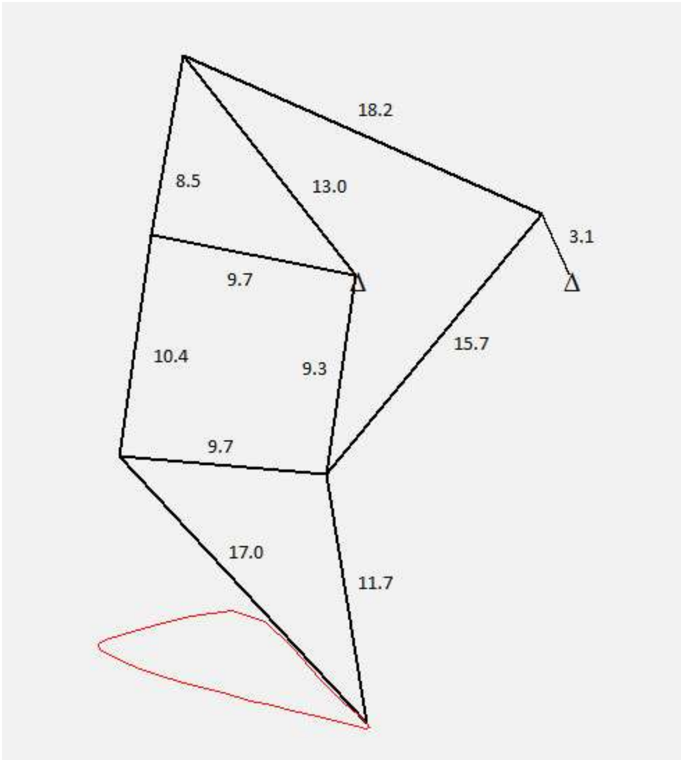


Four precision points corresponding to four specific crank angles.

This figure shows the mechanism in four different positions, corresponding to four crank angles. I wanted to adjust the 11 line segment lengths so that the toe point was as close as possible to the precision point for each of the four crank angles. The arrows I've drawn on the figure indicate where I want the toe point to be for each crank angle. Thus, the objective function is simply the sum of the distances between the actual toe point and the precision point. This is the quantity I want to minimize. In an optimal solution, that sum would be zero, meaning that the toe point passes exactly through each precision point.

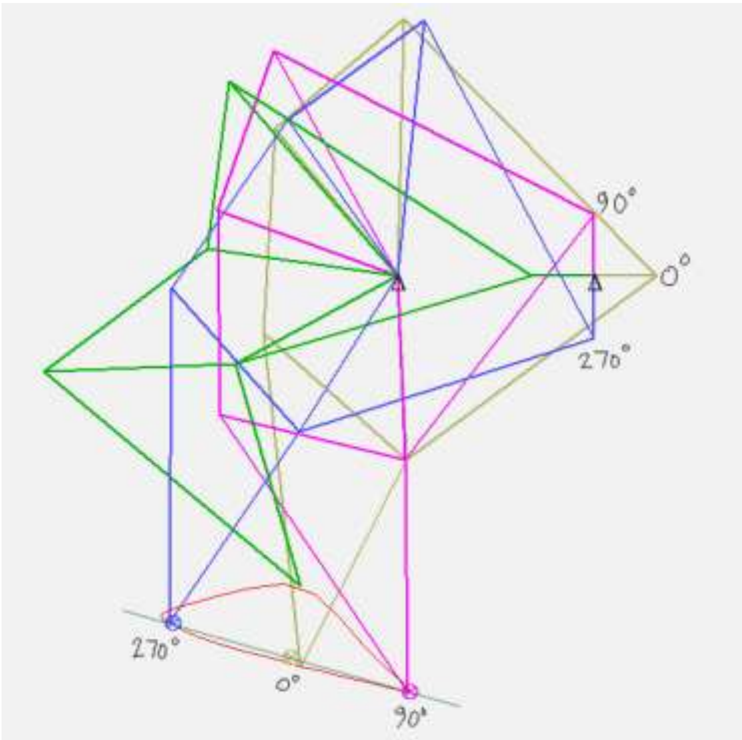
The constraints I defined for this optimization ensure that the area of each triangular region will not collapse to zero. In other words, wherever there are three line segments that form a triangle, the sum of the lengths of any two segments must be greater than the length of the third segment. This helps the optimizer from wandering into regions of the design space that contain defective mechanisms.

Numerical optimization is more of an art than a science, in my opinion. Usually, the process requires some intervention to prevent the process from exploiting mathematically valid, but physically meaningless excursions into the design space. I prefer to monitor the optimization process and cherry-pick fortuitous events, while rejecting obviously bad moves. In this case, the first iteration of the optimization process gave rise to a nice-looking toe path. Further iterations led to less desirable shapes. Here is the result of the first optimization iteration:



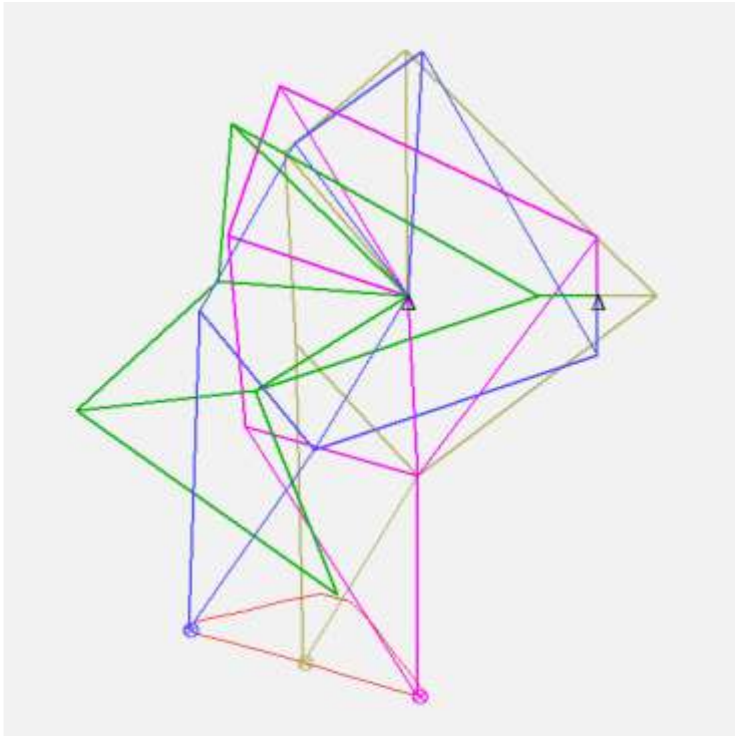
The result of the first optimization iteration.

Although the toe path is not very close to the desired precision points, it has nice characteristics when viewing the mechanism in a rotated configuration. I wanted to flatten out the lower portion of the toe path, so I defined some new precision points:



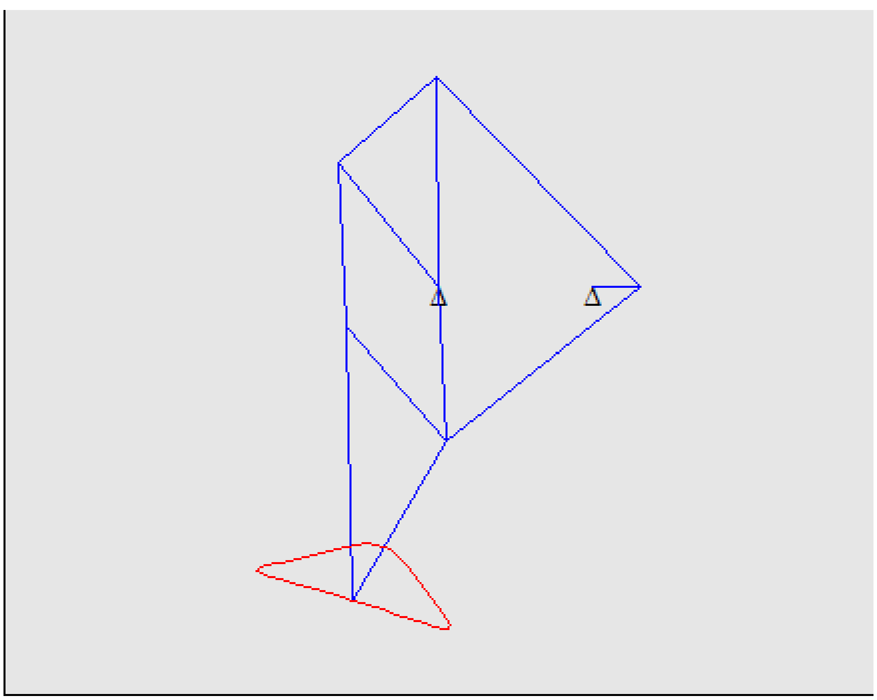
Precision points for the second optimization iteration.

These new precision points formed a straight line with equal spacing over 90 degree crank rotation. After a few more optimization iterations, I arrived at this design:



The result of re-running the optimization with the new precision points.

The lower portion of the toe path is now delightfully flat and encompasses a full half-turn of the input crank. Plus, the toe raises a good distance above the flat portion during the other half-turn of the crank, which will help the device step over obstacles. Here is an animated GIF of this final design:

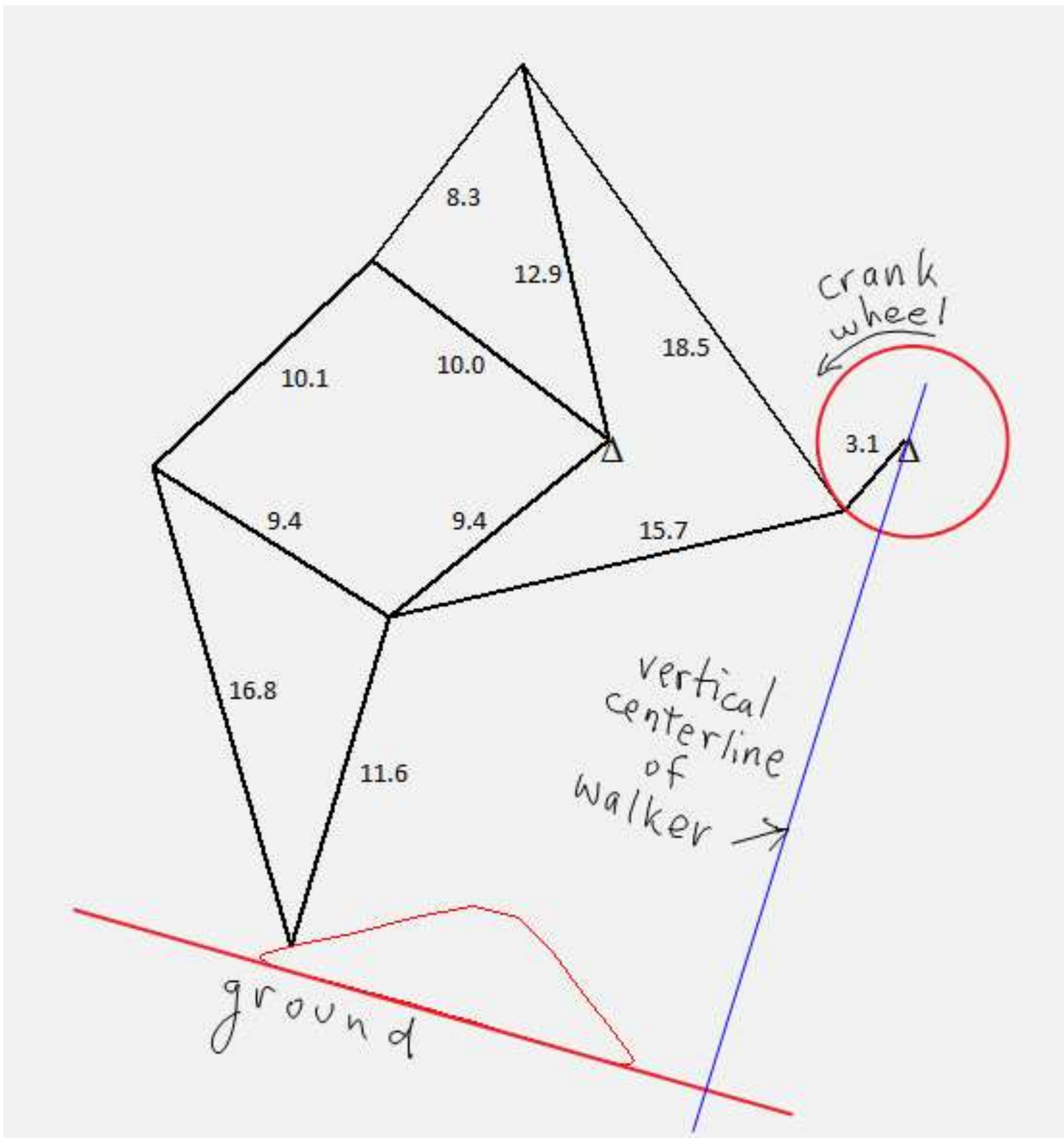


Animation of final design (click image link to animate).

Stability

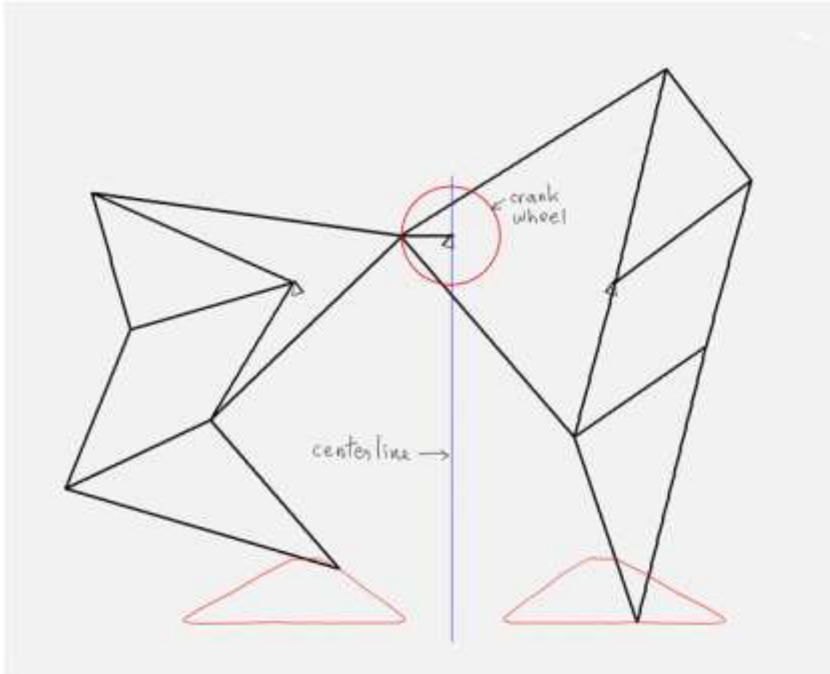
As mentioned earlier, most re-designs of Theo Jansen's walker require many parallel leg mechanisms because the "flat" portion of the toe path is actually somewhat curved. Overall stability of walking is achieved by having each leg in contact with the ground over a relatively small interval of the crank rotation. My design allows stable balance when only two legs are in contact with the ground, assuming the legs are wide enough to satisfy a static equilibrium condition. But I'm getting ahead of myself. First, let's talk about how to arrange the four legs.

Here are the line segment lengths for the optimal design:



Line segment lengths for the optimal design and ground plane.

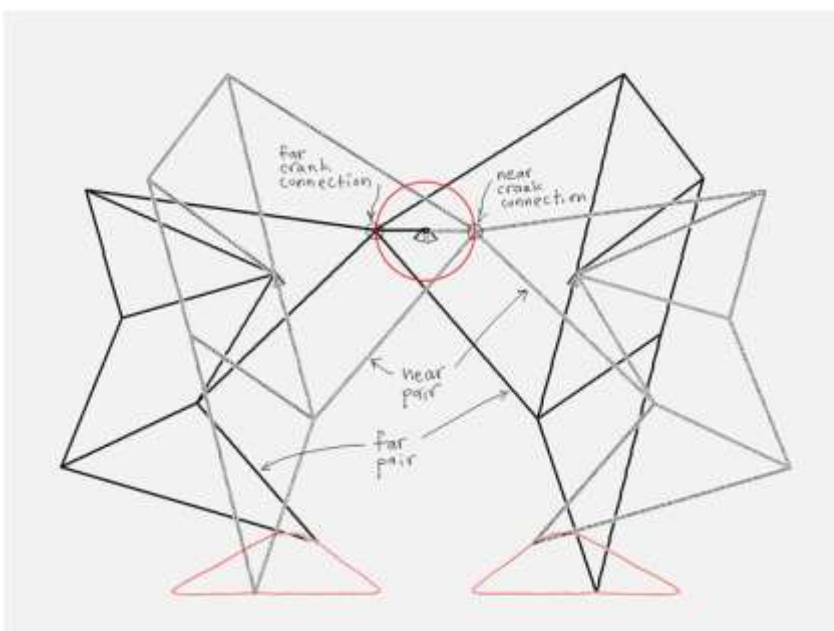
Theo Jansen's designs show how two legs can be placed side-by-side on the same crank, mirror images of one another, to produce a cooperative walking gait:



Two mirror-image legs on one crank eliminate one degree of instability.

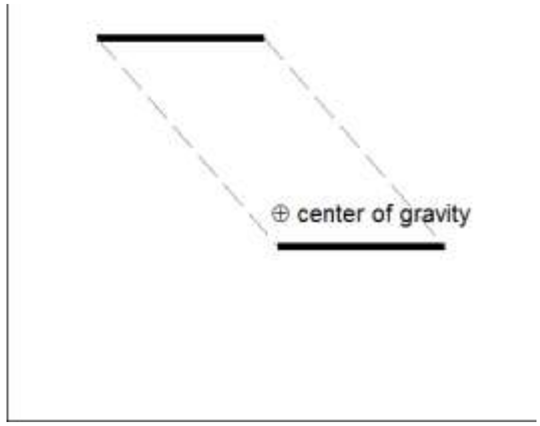
This eliminates on degree of walking instability by having one toe on the ground at all times. The mechanism was rotated 16.1 degrees in order to make the flat part of the toe path horizontal. Before rotation, recall that the two support pivots were 10 units apart horizontally. After rotation, the horizontal distance between the central leg pivot and the vertical centerline becomes 10*cos(16.1 deg)=9.61 and the vertical distance between the two pivots becomes 10*sin(16.1 deg)=2.77.

Another degree of instability is eliminated by having two pairs of legs working together, 180 degrees out of phase:



Full stability achieved by having two pairs of legs, 180 degrees out of phase.

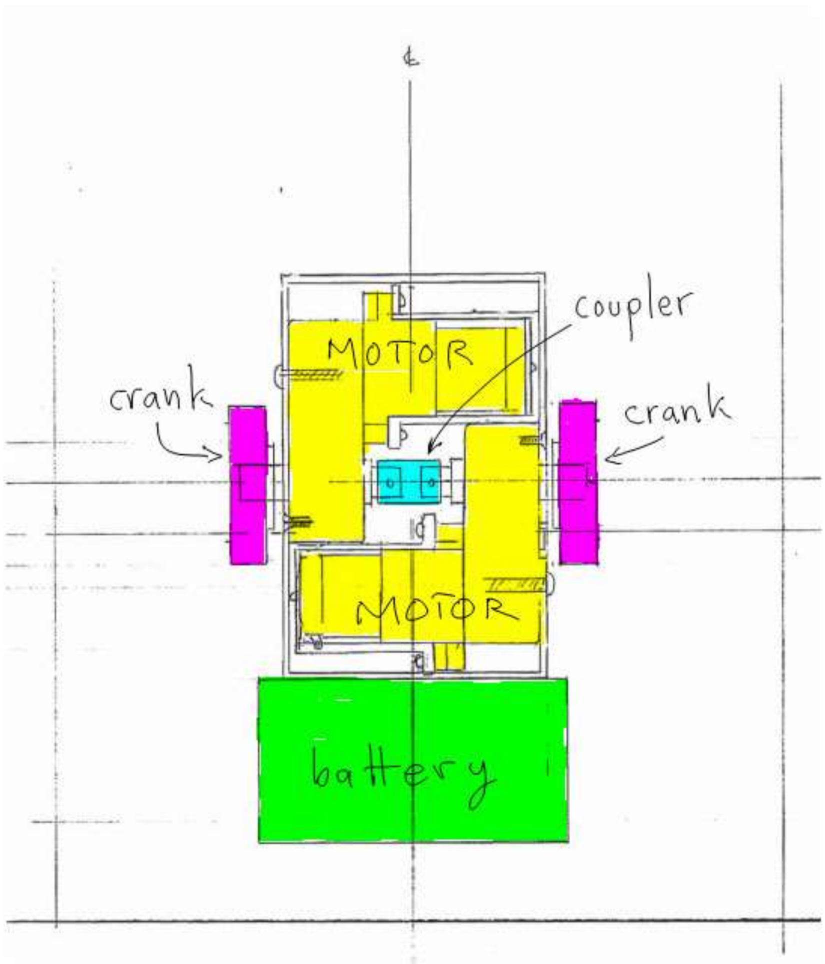
At any instant, there are two toe points in contact with the ground. By making the toe link sufficiently wide, the parallelogram formed by the two lines of toe contact always contains the center of gravity of the walker, thus ensuring static stability, as shown in this animated GIF:



Top view of lines of toe contact, enclosing the center of gravity at all instants. (Click image link to animate.)

Construction

Two gear motors drive the two crank wheels. The motors have drive shafts that protrude from both sides, so they can be coordinated to move together by using a shaft coupler:



A frontside view of the central body of the device.

The motors are oppositely wired so that they turn the two crank wheels in the same direction. A battery pack (4 AA) is suspended from below the body.

The leg mechanisms are cut by hand from sheets of 1/8″ Sintra (expanded PCV) board. The hinges are formed from gaffer tape and the shafts (1/16″ brass rod) pass through teflon tubing hot glued to the Sintra. The four links that connect to the crank wheels are 1/16″ brass rods with an eyelet bent by hand on each end.

In a subsequent project, I was also able to create this walking device using a 3D printer instead of building it from hand cut pieces.
