Assignment 2

Team 7

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Define the System Model

Our system model can be seen in figure 4 when we go through the stages of our XML. A preview of that image can be seen here. This model has four motors pulling and pushing on the robot, creating the movement that our team desires.

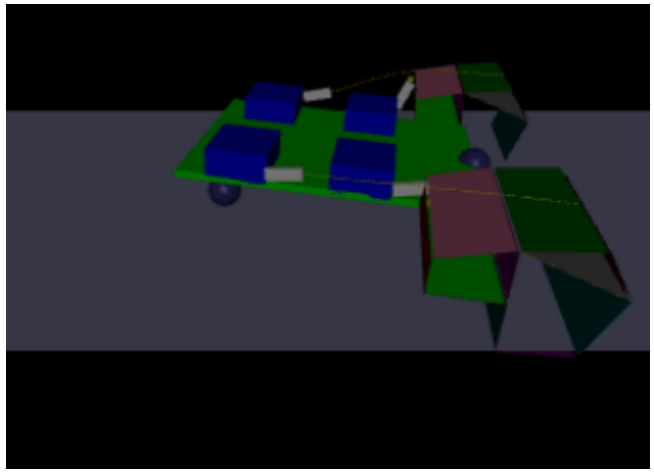


Fig.4 : After the Prototype

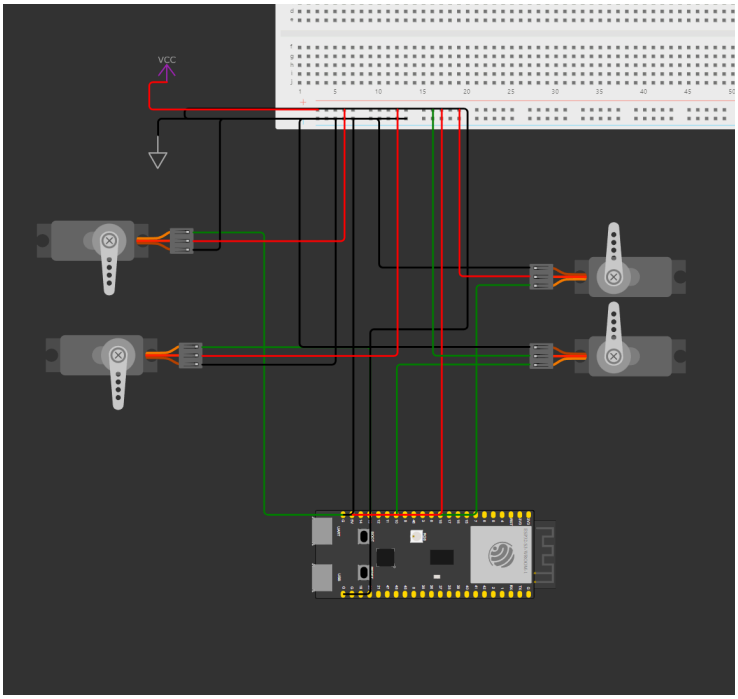


Fig.1 : Schematic with ESP32 and Servos

Optimize the Design

1. Frequency:

- Impact:
  - Speed: Higher frequencies generally lead to faster locomotion speeds.
  - Stability: Too high a frequency can destabilize the robot, causing it to vibrate excessively or lose balance.
  - Energy Consumption: Higher frequencies often require more energy input.
  - Terrain Adaptation: The optimal frequency can vary depending on the terrain. For example, rough terrain might require lower frequencies for better traction.
- Study:
  - Method: Vary the frequency of leg movements within a reasonable range.
  - Metrics: Measure forward speed, energy consumption, stability (e.g., number of falls), and ability to traverse different terrains.

2. Leg Weights:

- Impact:
  - Traction: Heavier legs can provide better traction, especially on slippery or uneven surfaces.
  - Maneuverability: Heavier legs can make it more difficult to change direction quickly.
  - Energy Consumption: Heavier legs require more energy to lift and swing.
  - Wear and Tear: Heavier legs can increase wear and tear on the robot's joints and motors.
- Study:
  - Method: Vary the weight of each leg individually or collectively.
  - Metrics: Measure traction, maneuverability, energy consumption, and wear and tear on the robot's components.

3. Phase Difference:

- Impact:
  - Gait Patterns: The phase difference between leg movements determines the robot's gait (e.g., walking, trotting, galloping).

    - Stability: Proper phase differences are crucial for maintaining balance and stability.
    - Maneuverability: Different phase differences can affect the robot's turning radius and agility.
    - Energy Efficiency: Certain phase differences may be more energy-efficient than others.
- Study:
    - Method: Systematically vary the phase difference between each leg's movement cycle.
    - Metrics: Analyze gait patterns, stability, maneuverability, and energy consumption.

plot your results.

Discussion for this

How does performance change in your in real-life?

Discuss any similarities or differences

As requested there are the three XMLs that were created throughout this process, including the model that each XML made.

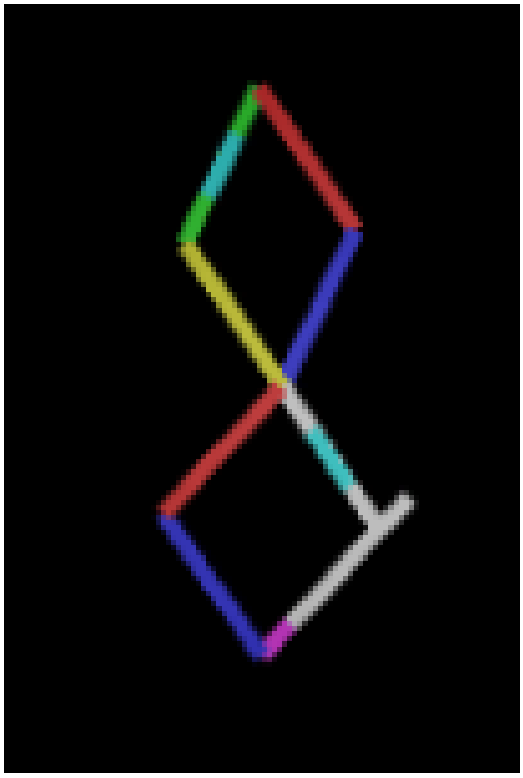


Fig. 2: Initial Mujoco Model

```
"""
<mujoco>
    <compiler angle="degree"/>
    <option><flag contact="disable"/></option>
    <worldbody>
        <!-- Setting up visuals -->
        <light name="top" pos="0 0 1"/>
        <camera name="world" pos="1 -8 -1" quat=".707 .707 0 0"/>
```

```
<!-- Knee Four Bar -->

<!-- Fixed Link -->
<body name="L1" pos="0 0 0" axisangle="0 1 0 -65">
   <geom type="box" size="{l1_size}" pos="{l1_gpos}" rgba="0 1 0 1" mass="1"/>

   <body name="L2" pos="{l2_bpos}" axisangle="0 1 0 80">
      <joint name="J2" type="hinge" axis="0 1 0" pos="0 0 0" damping=".5"/>
      <geom type="box" size="{l2_size}" pos="{l2_gpos}" rgba="1 0 0 1" mass="1"/>

      <body name="L3" pos="{l3_bpos}" axisangle="0 1 0 80">
         <joint name="J3" type="hinge" axis="0 1 0" pos="0 0 0" damping=".1"/>
         <geom type="box" size="{l3_size}" pos="{l3_gpos}" rgba="0 0 1 1" mass="1"/>

         <body name="L4" pos="{l4_bpos}" axisangle="0 1 0 80">
            <joint name="J4" type="hinge" axis="0 1 0" pos="0 0 0" damping=".1"/>
            <geom type="box" size="{l4_size}" pos="{l4_gpos}" rgba="1 1 0 1" mass="1"/>

            <body name="bind1" pos="{w1_bpos}" axisangle="0 1 0 80">
               <joint name="bj1" type="hinge" axis="0 1 0" pos="0 0 0" damping=".1"/>
mass="1"/>     <geom type="box" size=".2 .05 .05" pos="{l1_gpos}" rgba="0 1 1 1"
            </body>


            <!-- Ankle Four Bar -->

            <body name="L5" pos="-{l5_bpos}">
```

```
mass="1"/>        <geom type="box" size="{l5_size}" pos="{l5_gpos}" rgba="1 1 1 1"

                  <body name="L6" pos="0 0 0" axisangle="0 1 0 90">
                     <joint name="J6" type="hinge" axis="0 1 0" pos="0 0 0" damping=".5"/>
mass="1"/>           <geom type="box" size="{l6_size}" pos="{l6_gpos}" rgba="1 0 1 1"

                     <body name="L7" pos="{l7_bpos}" axisangle="0 1 0 90">
                        <joint name="J7" type="hinge" axis="0 1 0" pos="0 0 0" damping=".1"/>
mass="1"/>              <geom type="box" size="{l7_size}" pos="{l7_gpos}" rgba="0 0 1 1"

                        <body name="L8" pos="{l8_bpos}" axisangle="0 1 0 90">
damping=".1"/>             <joint name="J8" type="hinge" axis="0 1 0" pos="0 0 0"
mass="1"/>                 <geom type="box" size="{l8_size}" pos="{l8_gpos}" rgba="1 0 0 1"

                           <body name="bind2" pos="{w2_bpos}" axisangle="0 1 0 90">
damping=".1"/>                <joint name="bj2" type="hinge" axis="0 1 0" pos="0 0 0"
mass="1"/>                    <geom type="box" size=".2 .05 .05" pos="{l5_gpos}" rgba="0 1 1 1"

                           </body>
                        </body>
                     </body>

                     <body name="foot" pos="{f_bpos}">
mass="0"/>              <geom type="box" size="{f_size}" pos="{f_gpos}" rgba="1 1 1 1"
                     </body>
                  </body>
               </body>
```

```
                </body>
            </body>
        </body>
    </body>

  </worldbody>

  <equality>
    <weld name="weld1" active="true" body1="L1" body2="bind1" relpose="0 0 0 1 0 0 0"
anchor="{w1_anchor}"/>
    <weld name="weld2" active="true" body1="L5" body2="bind2" relpose="0 0 0 0 0 .894
-.448" anchor="{w2_anchor}"/>
  </equality>

  <actuator>
     <position name="motor1" joint="J2" kp="100"/>
     <position name="motor2" joint="bj2" kp="100"/>
  </actuator>
</mujoco>
"""
```

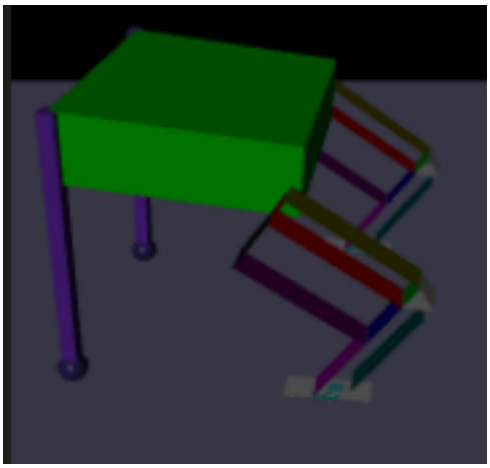


Fig. 3: Mujoco before assembling the prototype

```
"""
<mujoco>
   <compiler angle="degree"/>

   <worldbody>
      <camera name="world" pos="4 -10 8" euler="60 0 0"/>

      <!-- Ground -->
      <geom mass="0.1" name="ramp" type="plane" pos="0 0 0" size="50 10 0.1" euler="0 0 0"
rgba="0.7 0.7 .9 1" />

      <!-- Ostrich -->
      <body name="ostrich" pos="0 .2 0">

         <camera name="body_cam" mode="track" pos="0 -10 8" euler="60 0 0"/>
```

```
<joint type="hinge" axis="1 0 0" range="-35 35"/>
<joint type="hinge" axis="0 1 0" range="-45 45"/>
<joint type="slide" axis="0 0 1"/>
<joint type="slide" axis="0 1 0"/>
<joint type="slide" axis="1 0 0"/>

<!-- Rigid Body -->
<geom mass="0.1" name="body" type="box" size="1.5 1.5 .5" pos="0 0 3.5" euler="0 0
0" rgba="0 1 0 1" contype="0"/>

<geom mass="0.1"  name="rolling_leg_1" type="box" size=".1 .1 2" pos="-1.5 -1.5 2"
rgba=".5 .2 .9 1" contype="0"/>
<geom mass="0.5" name="wheel_1" type="sphere" size=".2" pos="-1.5 -1.5 0"
friction="0" rgba=".2 .2 .5 1"/>

<geom mass="0.1" name="rolling_leg_2" type="box" size=".1 .1 2" pos="-1.5 1.5 2"
rgba=".5 .2 .9 1" contype="0"/>
<geom mass="0.5" name="wheel_2" type="sphere" size=".2" pos="-1.5 1.5 0"
friction="0" rgba=".2 .2 .5 1"/>

<!-- Leg 1 -->

<body name="l1" pos="1 -1.8 2.8" axisangle="0 1 0 30">
   <!-- Fixed Link -->
   <geom mass="0.1" type="box" size=".0005 .2 {fixed}" pos="0 0 0" contype="0"
rgba=".1 .1 .1 1"/>
```

```
<!-- Four Bar 1, "Knee" -->
<body name="l1_b1_1" pos="0 0 {b1_1_b}" axisangle="0 1 0 {knee_angle}">
   <joint name="j1_b1_1" type="hinge" axis="0 1 0" pos="0 0 0" damping="0"
stiffness="0"/>
   <geom mass="0.1" type="box" size=".0005 .2 {b1_1}" pos="0 0 {b1_1_pos}"
rgba="1 0 0 1"/>

   <body name="l1_b1_2" pos="0 0 {b1_2_b}" axisangle="0 1 0 90">
      <joint name="j1_b1_2" type="hinge" axis="0 1 0" pos="0 0 0" damping="0"
stiffness="0"/>
      <geom mass="0.1" type="box" size=".0005 .2 {b1_2}" pos="0 0 {b1_2_pos}"
rgba="0 0 1 1"/>

      <body name="l1_b1_3" pos="0 0 {b1_3_b}" axisangle="0 1 0 90">
stiffness="0"/>   <joint name="j1_b1_3" type="hinge" axis="0 1 0" pos="0 0 0" damping="0"
rgba=".5 0 .5 1"/><geom mass="0.1" type="box" size=".0005 .2 {b1_3}" pos="0 0 {b1_3_pos}"

         <body name="l1_b1_4" pos="0 0 {b1_4_b}" axisangle="0 1 0 90">
stiffness="0"/>      <joint name="j1_b1_4" type="hinge" axis="0 1 0" pos="0 0 0" damping="0"
         <geom mass="0.1" type="box" size=".0005 .2 {b1_4}" pos="0 0
 {b1_4_pos}" rgba="0 0 1 0"/>

         </body>
      </body>
   </body>
```

```
</body>

<!-- Four Bar 2, Ankle Transfer -->
<body name="l1_b2_1" pos="0 0 {b2_1_b}" axisangle="0 1 0 {ankle_angle}">
   <joint name="j1_b2_1" type="hinge" axis="0 1 0" pos="0 0 0" damping="0"
 stiffness="0"/>
   <geom mass="0.1" type="box" size=".0005 .2 {b2_1}" pos="0 0 {b2_1_pos}"
rgba="1 0 0 1"/>

   <body name="l1_b2_2" pos="0 0 {b2_2_b}" axisangle="0 1 0 90">
stiffness="0"/><joint name="j1_b2_2" type="hinge" axis="0 1 0" pos="0 0 0" damping="0"
rgba=".5 .5 0 1"/><geom mass="0.1" type="box" size=".0005 .2 {b2_2}" pos="0 0 {b2_2_pos}"

      <body name="l1_b2_3" pos="0 0 {b2_3_b}" axisangle="0 1 0 90">
stiffness="0"/>  <joint name="j1_b2_3" type="hinge" axis="0 1 0" pos="0 0 0" damping="0"
rgba="0 1 0 1"/> <geom mass="0.1" type="box" size=".0005 .2 {b2_3}" pos="0 0 {b2_3_pos}"

      <body name="l1_b2_4" pos="0 0 {b2_4_b}" axisangle="0 1 0 90">
stiffness="0"/>    <joint name="j1_b2_4" type="hinge" axis="0 1 0" pos="0 0 0" damping="0"
      <geom mass="0.1" type="box" size=".0005 .2 {b2_4}" pos="0 0
{b2_4_pos}" rgba=".5 .5 0 0"/>

      </body>
   </body>
```

```
<!-- Transfer -->
<body name="l1_t_1" pos="0 0 {t_1_b}" axisangle="0 1 0 0">
stiffness="0"/>  <joint name="j1_t_1" type="hinge" axis="0 1 0" pos="0 0 0" damping="0"
rgba="1 1 1 1"/> <geom mass="0.1" type="box" size=".0005 .2 {t_1}" pos="0 0 {t_1_pos}"

<body name="l1_t_2" pos="0 0 {t_2_b}" axisangle="0 1 0 90">
stiffness="0"/>    <joint name="j1_t_2" type="hinge" axis="0 1 0" pos="0 0 0" damping="0"
rgba="1 1 1 1"/>   <geom mass="0.1" type="box" size=".0005 .2 {t_2}" pos="0 0 {t_2_pos}"

<body name="l1_t_3" pos="0 0 {t_3_b}" axisangle="0 1 0 90">
<joint name="j1_t_3" type="hinge" axis="0 1 0" pos="0 0 0"
damping="0" stiffness="0"/>
<geom mass="0.1" type="box" size=".0005 .2 {t_3}" pos="0 0
{t_3_pos}" rgba="1 1 1 0"/>

</body>
</body>

<!-- Four Bar 3, Ankle -->
<body name="l1_b3_1" pos="0 0 {b3_1_b}" axisangle="0 1 0 90">
<joint name="j1_b3_1" type="hinge" axis="0 1 0" pos="0 0 0" damping="0"
stiffness="0"/>
<geom mass="0.1" type="box" size=".0005 .2 {b3_1}" pos="0 0
{b3_1_pos}" rgba="0 .5 .5 1"/>
```

```
                    <body name="l1_b3_2" pos="0 0 {b3_2_b}" axisangle="0 1 0 90">
                        <joint name="j1_b3_2" type="hinge" axis="0 1 0" pos="0 0 0"
damping="0" range="-90 90" stiffness="0"/>
                        <geom mass="0.1" type="box" size=".0005 .2 {b3_2}" pos="0 0
{b3_2_pos}" rgba="0 1 1 1"/>

                        <!-- Foot -->
                        <geom mass="0.1" type="box" size=".0005 .2 .6" pos="0 0 .2"
friction=".36" rgba="1 1 1 1"/>

                        <body name="l1_b3_3" pos="0 0 {b3_3_b}" axisangle="0 1 0 90">
                            <joint name="j1_b3_3" type="hinge" axis="0 1 0" pos="0 0 0"
damping="0" stiffness="0"/>
                            <geom mass="0.1" type="box" size=".0005 .2 {b3_3}" pos="0 0
{b3_3_pos}" rgba="1 0 1 1" contype="0"/>

                        </body>
                    </body>
                </body>

            </body>

        </body>
    </body>

</body>
```

```
<!-- Leg 1 -->

 <body name="l2" pos="1 1.8 2.8" axisangle="0 1 0 30">
    <!-- Fixed Link -->
    <geom mass="0.1" type="box" size=".0005 .2 {fixed}" pos="0 0 0" contype="0"
rgba=".1 .1 .1 1"/>

    <!-- Four Bar 1, "Knee" -->
    <body name="l2_b1_1" pos="0 0 {b1_1_b}" axisangle="0 1 0 {knee_angle}">
      <joint name="j2_b1_1" type="hinge" axis="0 1 0" pos="0 0 0" damping="0"
stiffness="0"/>
      <geom mass="0.1" type="box" size=".0005 .2 {b1_1}" pos="0 0 {b1_1_pos}"
rgba="1 0 0 1"/>

      <body name="l2_b1_2" pos="0 0 {b1_2_b}" axisangle="0 1 0 90">
        <joint name="j2_b1_2" type="hinge" axis="0 1 0" pos="0 0 0" damping="0"
stiffness="0"/>
        <geom mass="0.1" type="box" size=".0005 .2 {b1_2}" pos="0 0 {b1_2_pos}"
rgba="0 0 1 1"/>

        <body name="l2_b1_3" pos="0 0 {b1_3_b}" axisangle="0 1 0 90">
          <joint name="j2_b1_3" type="hinge" axis="0 1 0" pos="0 0 0" damping="0"
stiffness="0"/>
          <geom mass="0.1" type="box" size=".0005 .2 {b1_3}" pos="0 0 {b1_3_pos}"
```

```
rgba=".5 0 .5 1"/>

                <body name="l2_b1_4" pos="0 0 {b1_4_b}" axisangle="0 1 0 90">
                  <joint name="j2_b1_4" type="hinge" axis="0 1 0" pos="0 0 0" damping="0"
stiffness="0"/>
                  <geom mass="0.1" type="box" size=".0005 .2 {b1_4}" pos="0 0
{b1_4_pos}" rgba="0 0 1 0"/>

                </body>
              </body>
            </body>
          </body>

          <!-- Four Bar 2, Ankle Transfer -->
          <body name="l2_b2_1" pos="0 0 {b2_1_b}" axisangle="0 1 0 {ankle_angle}">
            <joint name="j2_b2_1" type="hinge" axis="0 1 0" pos="0 0 0" damping="0"
stiffness="0"/>
            <geom mass="0.1" type="box" size=".0005 .2 {b2_1}" pos="0 0 {b2_1_pos}"
rgba="1 0 0 1"/>

            <body name="l2_b2_2" pos="0 0 {b2_2_b}" axisangle="0 1 0 90">
              <joint name="j2_b2_2" type="hinge" axis="0 1 0" pos="0 0 0" damping="0"
stiffness="0"/>
              <geom mass="0.1" type="box" size=".0005 .2 {b2_2}" pos="0 0 {b2_2_pos}"
rgba=".5 .5 0 1"/>
```

```
<body name="l2_b2_3" pos="0 0 {b2_3_b}" axisangle="0 1 0 90">
  <joint name="j2_b2_3" type="hinge" axis="0 1 0" pos="0 0 0" damping="0"
stiffness="0"/>
  <geom mass="0.1" type="box" size=".0005 .2 {b2_3}" pos="0 0 {b2_3_pos}"
rgba="0 1 0 1"/>

  <body name="l2_b2_4" pos="0 0 {b2_4_b}" axisangle="0 1 0 90">
    <joint name="j2_b2_4" type="hinge" axis="0 1 0" pos="0 0 0" damping="0"
stiffness="0"/>
    <geom mass="0.1" type="box" size=".0005 .2 {b2_4}" pos="0 0
{b2_4_pos}" rgba=".5 .5 0 0"/>

  </body>
</body>

<!-- Transfer -->
<body name="l2_t_1" pos="0 0 {t_1_b}" axisangle="0 1 0 0">
stiffness="0"/>  <joint name="j2_t_1" type="hinge" axis="0 1 0" pos="0 0 0" damping="0"
rgba="1 1 1 1"/> <geom mass="0.1" type="box" size=".0005 .2 {t_1}" pos="0 0 {t_1_pos}"

  <body name="l2_t_2" pos="0 0 {t_2_b}" axisangle="0 1 0 90">
stiffness="0"/>    <joint name="j2_t_2" type="hinge" axis="0 1 0" pos="0 0 0" damping="0"
rgba="1 1 1 1"/>   <geom mass="0.1" type="box" size=".0005 .2 {t_2}" pos="0 0 {t_2_pos}"

    <body name="l2_t_3" pos="0 0 {t_3_b}" axisangle="0 1 0 90">
```

```
<joint name="j2_t_3" type="hinge" axis="0 1 0" pos="0 0 0"
damping="0" stiffness="0"/>
<geom mass="0.1" type="box" size=".0005 .2 {t_3}" pos="0 0
{t_3_pos}" rgba="1 1 1 0"/>

</body>
</body>

<!-- Four Bar 3, Ankle -->
<body name="l2_b3_1" pos="0 0 {b3_1_b}" axisangle="0 1 0 90">
stiffness="0"/>  <joint name="j2_b3_1" type="hinge" axis="0 1 0" pos="0 0 0" damping="0"
<geom mass="0.1" type="box" size=".0005 .2 {b3_1}" pos="0 0
{b3_1_pos}" rgba="0 .5 .5 1"/>

<body name="l2_b3_2" pos="0 0 {b3_2_b}" axisangle="0 1 0 90">
<joint name="j2_b3_2" type="hinge" axis="0 1 0" pos="0 0 0"
damping="0" range="-90 90" stiffness="0"/>
<geom mass="0.1" type="box" size=".0005 .2 {b3_2}" pos="0 0
{b3_2_pos}" rgba="0 1 1 1"/>

<!-- Foot -->
<geom mass="0.1" type="box" size=".0005 .2 .6" pos="0 0 .2"
friction=".36" rgba="1 1 1 1"/>

<body name="l2_b3_3" pos="0 0 {b3_3_b}" axisangle="0 1 0 90">
<joint name="j2_b3_3" type="hinge" axis="0 1 0" pos="0 0 0"
```

```
damping="0" stiffness="0"/>
                                <geom mass="0.1" type="box" size=".0005 .2 {b3_3}" pos="0 0
{b3_3_pos}" rgba="1 0 1 1" contype="0"/>

                            </body>
                          </body>
                        </body>
                      </body>
                    </body>
                  </body>
                </body>
              </worldbody>

              <equality>
                <weld name="l1_4bar_1" active="true" body1="l1" body2="l1_b1_4" relpose="0 .025 -.4 1
0 0 0"/>
                <weld name="l1_4bar_2" active="true" body1="l1_b1_1" body2="l1_b2_4" relpose="0 0 2
0 0 1 0"/>
                <weld name="l1_t" active="true" body1="l1_b1_1" body2="l1_t_3" relpose="0 0 2 0 0 1
0"/>
                <weld name="l1_4bar_3" active="true" body1="l1_b3_3" body2="l1_b1_2" relpose="0 0 2
0 0 1 0"/>

                <weld name="l2_4bar_1" active="true" body1="l2" body2="l2_b1_4" relpose="0 .025 -.4 1
 0 0 0"/>
```

```
        <weld name="l2_4bar_2" active="true" body1="l2_b1_1" body2="l2_b2_4" relpose="0 0 2
 0 0 1 0"/>
        <weld name="l2_t" active="true" body1="l2_b1_1" body2="l2_t_3" relpose="0 0 2 0 0 1
0"/>
        <weld name="l2_4bar_3" active="true" body1="l2_b3_3" body2="l2_b1_2" relpose="0 0 2
 0 0 1 0"/>

    </equality>

    <actuator>
        <position name="l1_servo1" joint="j1_b1_1" kp="200"/>
        <position name="l1_servo2" joint="j1_b2_1" kp="200"/>

        <position name="l2_servo1" joint="j2_b1_1" kp="200"/>
        <position name="l2_servo2" joint="j2_b2_1" kp="200"/>

    </actuator>
</mujoco>

"""
```

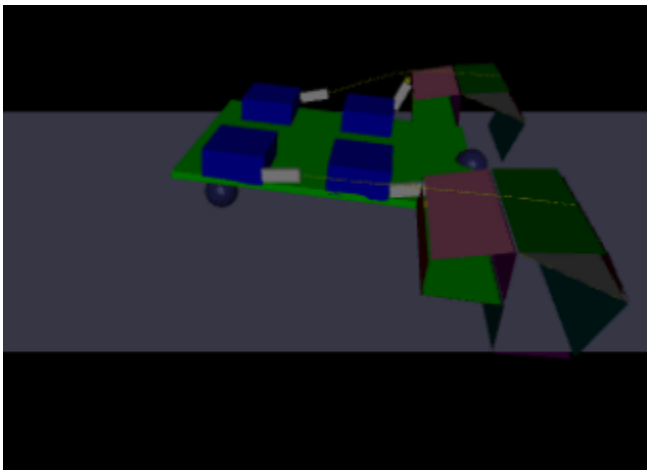


Fig. 4: After making a prototype

```
"""
<mujoco>
   <compiler angle="degree"/>
   <option><flag contact="enable"/></option>

   <worldbody>
      <camera name="world" pos="0 -22 10" euler="60 0 0"/>

      <!-- Ground -->
      <geom mass="0.1" name="ramp" type="plane" pos="0 0 0" size="50 10 0.1" euler="0 0 0"
rgba="0.7 0.7 .9 1" />

      <!-- Ostrich -->
      <body name="ostrich" pos="0 0 {wheel_radius}">

         <camera name="body_cam" mode="track" pos="0 -22 10" euler="60 0 0"/>
         <joint name="ostrich" type="free"/>
```

```
<!-- Rigid Body -->

<body name="rigid_legs">
    <geom mass="0.1"  name="rolling_leg_1" type="box" size=".1 .1 {still_leg_z}"
 pos="{still_leg_x} -{still_leg_y} {still_leg_z}" rgba=".5 .2 .9 1" contype="0"/>
    <geom mass="0.5" name="wheel_1" type="sphere" size="{wheel_radius}"
pos="{still_leg_x} -{still_leg_y} 0" friction="0" rgba=".2 .2 .5 1"/>

    <geom mass="0.1" name="rolling_leg_2" type="box" size=".1 .1 {still_leg_z}"
 pos="{still_leg_x} {still_leg_y} {still_leg_z}" rgba=".5 .2 .9 1" contype="0"/>
    <geom mass="0.5" name="wheel_2" type="sphere" size="{wheel_radius}"
pos="{still_leg_x} {still_leg_y} 0" friction="0" rgba=".2 .2 .5 1"/>

</body>

<body name="body" pos="0 0 {body_height}">
    <geom mass="0.02" name="body" type="box" size="{body_length} {body_width}
.125" pos="0 0 0" euler="0 0 0" rgba="0 1 0 1" contype="0"/>
    <geom mass=".002" name="wheel_3" type="sphere" size="{wheel_radius}"
pos="{body_length} 0 0" friction="0" rgba=".2 .2 .5 1"/>

    <!-- Leg 1 -->

    <body name="l1" pos="{leg_x} -{leg_y} {leg_z}" axisangle="0 1 0 180">

      <!-- Fixed Link -->
      <geom mass="0.001" type="box" size="{fixed} {bar_width} .0005" pos="0 0 0"
```

```
contype="1" rgba=".1 .1 .1 1"/>


        <!-- Four Bar 1, "Knee" -->
        <body name="l1_b1_1" pos="{b1_1_b} 0 0" axisangle="0 1 0 95">
          <joint name="j1_b1_1" type="hinge" axis="0 1 0" pos="0 0 0" damping="0"
range="-140 90" stiffness="0"/>
          <geom mass="0.001" type="box" size="{b1_1} {bar_width} .0005"
pos="{b1_1_pos} 0 0" rgba="1 0 0 1"/>

          <body name="l1_b1_2" pos="{b1_2_b} 0 0" axisangle="0 1 0 95">
            <joint name="j1_b1_2" type="hinge" axis="0 1 0" pos="0 0 0" damping="0"
range="-140 90" stiffness="0"/>
            <geom mass="0.001" type="box" size="{b1_2} {bar_width} .0005"
pos="{b1_2_pos} 0 0" rgba="1 .5 .7 1"/>

            <body name="l1_b1_3" pos="{b1_3_b} 0 0" axisangle="0 1 0 95">
              <joint name="j1_b1_3" type="hinge" axis="0 1 0" pos="0 0 0" damping="0"
range="-140 90" stiffness="0"/>
              <geom mass="0.001" type="box" size="{b1_3} {bar_width} .0005"
 pos="{b1_3_pos} 0 0" rgba="1 0 1 1"/>

              <body name="l1_b1_4" pos="{b1_4_b} 0 0" axisangle="0 1 0 95">
                <joint name="j1_b1_4" type="hinge" axis="0 1 0" pos="0 0 0"
damping="0" range="-140 90" stiffness="0"/>
                <geom mass="0.001" type="box" size="{b1_4} {bar_width} .0005"
pos="{b1_4_pos} 0 0" rgba="0 1 0 1"/>
```

```
            </body>
        </body>

        <!-- Four Bar 2, "Ankle" -->
        <body name="l1_b2_1" pos="{b2_1_b} 0 0" axisangle="0 1 0 0">
            <joint name="j1_b2_1" type="hinge" axis="0 1 0" pos="0 0 0"
damping="0.3" range="45 -45" stiffness="0.4"/>
            <geom mass="0.001" type="box" size="{b2_1} {bar_width} .0005"
pos="{b2_1_pos} 0 0" rgba="0.5 0.5 0.5 1"/>

            <body name="l1_b2_2" pos="{b2_2_b} 0 0" axisangle="0 1 0 95">
                <joint name="j1_b2_2" type="hinge" axis="0 1 0" pos="0 0 0"
damping="0.3" range="45 -45" stiffness="0.4"/>
                <geom mass="0.001" type="box" size="{b2_2} {bar_width} .0005"
 pos="{b2_2_pos} 0 0" rgba="0 0.5 0.5 1"/>

                <body name="l1_b2_3" pos="{b2_3_b} 0 0" axisangle="0 1 0 95">
                    <joint name="j1_b2_3" type="hinge" axis="0 1 0" pos="0 0 0"
damping="0.3" range="45 -45" stiffness="0.4"/>
                    <geom mass="{foot_mass}" type="box" size="{b2_3} {bar_width}
 .0005" pos="{b2_3_pos} 0 0" friction=".41" rgba="0.5 0 0.5 1"/>

                    <body name="l1_b2_4" pos="{b2_4_b} 0 0" axisangle="0 1 0 95">
                        <joint name="j1_b2_4" type="hinge" axis="0 1 0" pos="0 0 0"
damping="0.3" range="45 -45" stiffness="0.4"/>
                        <geom mass="0.001" type="box" size="{b2_4} {bar_width} .0005"
pos="{b2_4_pos} 0 0" rgba="0 0.5 0.5 1"/>
```

```
            </body>
        </body>
    </body>
</body>

<!-- Transfer -->
<body name="l1_t_1" pos="{t_1_b} 0 0" axisangle="0 1 0 0">
stiffness="0"/>     <joint name="j1_t_1" type="hinge" axis="0 1 0" pos="0 0 0" damping="0"
    <geom mass="0.001" type="box" size="{t_1} {bar_width} .0005"
pos="{t_1_pos} 0 0" rgba="0 0.5 0 1"/>

    <body name="l1_t_2" pos="{t_2_b} 0 0" axisangle="0 1 0 60">
        <joint name="j1_t_2" type="hinge" axis="0 1 0" pos="0 0 0"
damping="0" range="-45 180" stiffness="0"/>
        <geom mass="0.001" type="box" size="{t_2} {bar_width} .0005"
pos="{t_2_pos} 0 0" rgba="0.5 0 0 1"/>

        <body name="l1_t_3" pos="{t_3_b} 0 0" axisangle="0 1 0 100">
damping="0" stiffness="0"/>     <joint name="j1_t_3" type="hinge" axis="0 1 0" pos="0 0 0"
            <geom mass="0.001" type="box" size="{t_3} {bar_width} .0005"
pos="{t_3_pos} 0 0" rgba="1 1 0 1"/>


        </body>
    </body>
```

```
                </body>



            </body>
        </body>

    </body>

    <!-- Knee Motors -->
    <body name="l1_knee_Servo" pos="{knee_servo_x} -{knee_servo_y}
{knee_servo_z}">
        <geom mass="0.01" type="box" size="{servo_length} {servo_width}
{servo_height}" pos="0 0 0" rgba="0 0 1 1"/>

        <body name="l1_knee_horn" pos="{servo_length} -{servo_horn_pos} 0"
axisangle="0 1 0 0">
            <joint name="j1_ks_horn" type="hinge" axis="0 1 0" pos="0 0 0" damping="0"
stiffness="0" range="-90 90"/>
            <geom mass="0.001" type="box" size="{horn_length} {horn_width}
{horn_height}" pos="{servo_horn_x} 0 0" rgba="1 1 1 1"/>

            <body name="l1_ks_1" pos="{ks_1_b} 0 0" axisangle="0 1 0 -5">
                <joint name="j1_ks_1" type="ball" damping="0.6"/>
                <geom mass="0.001" type="box" size="{ks_1} .01 .01" pos="{ks_1_pos} 0 0"
contype="1" rgba="1 1 0 1"/>

                <body name="l1_ks_2" pos="{ks_2_b} 0 0" axisangle="0 1 0 -5">
                    <joint name="j1_ks_2" type="ball" damping="0.6"/>
```

```
<geom mass="0.001" type="box" size="{ks_2} .01 .01" pos="{ks_2_pos} 0
 0" contype="1" rgba="1 1 0 1"/>

<body name="l1_ks_3" pos="{ks_3_b} 0 0" axisangle="0 1 0 -5">
  <joint name="j1_ks_3" type="ball" damping="0.6"/>
  <geom mass="0.001" type="box" size="{ks_3} .01 .01" pos="{ks_3_pos}
0 0" contype="1" rgba="1 1 0 1"/>

  <body name="l1_ks_4" pos="{ks_4_b} 0 0" axisangle="0 1 0 -5">
    <joint name="j1_ks_4" type="ball" damping="0.6"/>
    <geom mass="0.001" type="box" size="{ks_4} .01 .01"
pos="{ks_4_pos} 0 0" contype="1" rgba="1 1 0 1"/>

    <body name="l1_ks_5" pos="{ks_5_b} 0 0" axisangle="0 1 0 -5">
      <joint name="j1_ks_5" type="ball" damping="0.6"/>
      <geom mass="0.001" type="box" size="{ks_5} .01 .01"
pos="{ks_5_pos} 0 0" contype="1" rgba="1 1 0 1"/>

      <body name="l1_ks_6" pos="{ks_6_b} 0 0" axisangle="0 1 0 -5">
        <joint name="j1_ks_6" type="ball" damping="0.6"/>
        <geom mass="0.1" type="box" size="{ks_6} {bar_width} .0005"
 pos="{ks_6_pos} 0 0" rgba="0.5 0 0 1"/>
      </body>
    </body>
  </body>
</body>
</body>
</body>
```

```
            </body>
          </body>

          <body name="l1_ankle_Servo" pos="{ankle_servo_x} -{ankle_servo_y}
{ankle_servo_z}">
            <geom mass="0.01" type="box" size="{servo_length} {servo_width}
 {servo_height}" pos="0 0 0" rgba="0 0 1 1"/>

            <body name="l1_ankle_horn" pos="{servo_length} -{servo_horn_pos} 0"
axisangle="0 1 0 -90">
stiffness="0"/><joint name="j1_as_horn" type="hinge" axis="0 1 0" pos="0 0 0" damping="0"
              <geom mass="0.001" type="box" size="{horn_length} {horn_width}
{horn_height}" pos="{servo_horn_x} 0 0" rgba="1 1 1 1"/>

              <body name="l1_as_rod" pos="{as_rod_b} 0 0" axisangle="0 1 0 90">
                <joint name="j1_as_rod" type="hinge" axis="0 1 0" damping="0"
stiffness="0.3"/>
                <geom mass="0.0001" type="box" size="{as_rod} .1 .1" pos="{as_rod_pos}
 -1 0" contype="1" rgba="1 1 0 1"/>

                <body name="l1_as_1" pos="{as_1_b} 0 0" axisangle="0 1 0 90">
                  <joint name="j1_as_1" type="ball" damping="0"/>
                  <geom mass="0.001" type="box" size="{as_1} {bar_width} .0005"
 pos="{as_1_pos} -{bar_width} 0" contype="0" rgba="1 0 0 0"/>

                </body>
              </body>
            </body>
```

```
</body>


<!-- Leg 2 -->

<body name="l2" pos="{leg_x} {leg_y} {leg_z}" axisangle="0 1 0 180">

  <!-- Fixed Link -->
  <geom mass="0.001" type="box" size="{fixed} {bar_width} .0005" pos="0 0 0"
contype="1" rgba=".1 .1 .1 1"/>


  <!-- Four Bar 1, "Knee" -->
  <body name="l2_b1_1" pos="{b1_1_b} 0 0" axisangle="0 1 0 95">
    <joint name="j2_b1_1" type="hinge" axis="0 1 0" pos="0 0 0" damping="0"
 range="-90 90" stiffness="0"/>
    <geom mass="0.001" type="box" size="{b1_1} {bar_width} .0005"
pos="{b1_1_pos} 0 0" rgba="1 0 0 1"/>

    <body name="l2_b1_2" pos="{b1_2_b} 0 0" axisangle="0 1 0 95">
      <joint name="j2_b1_2" type="hinge" axis="0 1 0" pos="0 0 0" damping="0"
range="-90 90" stiffness="0"/>
      <geom mass="0.001" type="box" size="{b1_2} {bar_width} .0005"
pos="{b1_2_pos} 0 0" rgba="1 .5 .7 1"/>

      <body name="l2_b1_3" pos="{b1_3_b} 0 0" axisangle="0 1 0 95">
        <joint name="j2_b1_3" type="hinge" axis="0 1 0" pos="0 0 0" damping="0"
range="-90 90" stiffness="0"/>
```

```
                <geom mass="0.001" type="box" size="{b1_3} {bar_width} .0005"
pos="{b1_3_pos} 0 0" rgba="1 0 1 1"/>

                <body name="l2_b1_4" pos="{b1_4_b} 0 0" axisangle="0 1 0 95">
                  <joint name="j2_b1_4" type="hinge" axis="0 1 0" pos="0 0 0"
damping="0" range="-90 90" stiffness="0"/>
                  <geom mass="0.001" type="box" size="{b1_4} {bar_width} .0005"
pos="{b1_4_pos} 0 0" rgba="0 1 0 1"/>


                </body>
              </body>

              <!-- Four Bar 2, "Ankle" -->
              <body name="l2_b2_1" pos="{b2_1_b} 0 0" axisangle="0 1 0 0">
                <joint name="j2_b2_1" type="hinge" axis="0 1 0" pos="0 0 0"
damping="0.3" range="45 -45" stiffness="0.4"/>
                <geom mass="0.001" type="box" size="{b2_1} {bar_width} .0005"
 pos="{b2_1_pos} 0 0" rgba="0.5 0.5 0.5 1"/>

                <body name="l2_b2_2" pos="{b2_2_b} 0 0" axisangle="0 1 0 95">
                  <joint name="j2_b2_2" type="hinge" axis="0 1 0" pos="0 0 0"
damping="0.3" range="45 -45" stiffness="0.4"/>
                  <geom mass="0.001" type="box" size="{b2_2} {bar_width} .0005"
 pos="{b2_2_pos} 0 0" rgba="0 0.5 0.5 1"/>

                  <body name="l2_b2_3" pos="{b2_3_b} 0 0" axisangle="0 1 0 95">
                    <joint name="j2_b2_3" type="hinge" axis="0 1 0" pos="0 0 0"
```

```
damping="0.3" range="45 -45" stiffness="0.4"/>
                    <geom mass="{foot_mass}" type="box" size="{b2_3} {bar_width}
.0005" pos="{b2_3_pos} 0 0" friction=".41" rgba="0.5 0 0.5 1"/>

                    <body name="l2_b2_4" pos="{b2_4_b} 0 0" axisangle="0 1 0 95">
                      <joint name="j2_b2_4" type="hinge" axis="0 1 0" pos="0 0 0"
 damping="0.3" range="45 -45" stiffness="0.4"/>
                      <geom mass="0.001" type="box" size="{b2_4} {bar_width} .0005"
 pos="{b2_4_pos} 0 0" rgba="0 0.5 0.5 1"/>

                    </body>
                  </body>
                </body>
              </body>

              <!-- Transfer -->
              <body name="l2_t_1" pos="{t_1_b} 0 0" axisangle="0 1 0 0">
stiffness="0"/>     <joint name="j2_t_1" type="hinge" axis="0 1 0" pos="0 0 0" damping="0"
                    <geom mass="0.001" type="box" size="{t_1} {bar_width} .0005"
 pos="{t_1_pos} 0 0" rgba="0 0.5 0 1"/>

                    <body name="l2_t_2" pos="{t_2_b} 0 0" axisangle="0 1 0 60">
                      <joint name="j2_t_2" type="hinge" axis="0 1 0" pos="0 0 0"
 damping="0" range="-45 180" stiffness="0"/>
                      <geom mass="0.001" type="box" size="{t_2} {bar_width} .0005"
pos="{t_2_pos} 0 0" rgba="0.5 0 0 1"/>

                      <body name="l2_t_3" pos="{t_3_b} 0 0" axisangle="0 1 0 100">
```

```
damping="0" stiffness="0"/>
                    <joint name="j2_t_3" type="hinge" axis="0 1 0" pos="0 0 0"
                        <geom mass="0.001" type="box" size="{t_3} {bar_width} .0005"
 pos="{t_3_pos} 0 0" rgba="1 1 0 1"/>


                    </body>
                  </body>
                </body>


              </body>
            </body>

          </body>

          <!-- Knee Motors -->
          <body name="l2_knee_Servo" pos="{knee_servo_x} {knee_servo_y}
 {knee_servo_z}">
            <geom mass="0.01" type="box" size="{servo_length} {servo_width}
{servo_height}" pos="0 0 0" rgba="0 0 1 1"/>

            <body name="l2_knee_horn" pos="{servo_length} {servo_horn_pos} 0"
axisangle="0 1 0 0">
              <joint name="j2_ks_horn" type="hinge" axis="0 1 0" pos="0 0 0" damping="0"
 stiffness="0" range="-90 90"/>
              <geom mass="0.001" type="box" size="{horn_length} {horn_width}
{horn_height}" pos="{servo_horn_x} 0 0" rgba="1 1 1 1"/>
```

```
<body name="l2_ks_1" pos="{ks_1_b} 0 0" axisangle="0 1 0 -5">
  <joint name="j2_ks_1" type="ball" damping="0.6"/>
  <geom mass="0.001" type="box" size="{ks_1} .01 .01" pos="{ks_1_pos} 0 0"
contype="1" rgba="1 1 0 1"/>

  <body name="l2_ks_2" pos="{ks_2_b} 0 0" axisangle="0 1 0 -5">
    <joint name="j2_ks_2" type="ball" damping="0.6"/>
    <geom mass="0.001" type="box" size="{ks_2} .01 .01" pos="{ks_2_pos} 0
0" contype="1" rgba="1 1 0 1"/>

    <body name="l2_ks_3" pos="{ks_3_b} 0 0" axisangle="0 1 0 -5">
      <joint name="j2_ks_3" type="ball" damping="0.6"/>
      <geom mass="0.001" type="box" size="{ks_3} .01 .01" pos="{ks_3_pos}
0 0" contype="1" rgba="1 1 0 1"/>

      <body name="l2_ks_4" pos="{ks_4_b} 0 0" axisangle="0 1 0 -5">
        <joint name="j2_ks_4" type="ball" damping="0.6"/>
        <geom mass="0.001" type="box" size="{ks_4} .01 .01"
 pos="{ks_4_pos} 0 0" contype="1" rgba="1 1 0 1"/>

        <body name="l2_ks_5" pos="{ks_5_b} 0 0" axisangle="0 1 0 -5">
          <joint name="j2_ks_5" type="ball" damping="0.6"/>
          <geom mass="0.001" type="box" size="{ks_5} .01 .01"
pos="{ks_5_pos} 0 0" contype="1" rgba="1 1 0 1"/>

          <body name="l2_ks_6" pos="{ks_6_b} 0 0" axisangle="0 1 0 -5">
            <joint name="j2_ks_6" type="ball" damping="0.6"/>
            <geom mass="0.1" type="box" size="{ks_6} {bar_width} .0005"
```

```
pos="{ks_6_pos} 0 0" rgba="0.5 0 0 1"/>


                    </body>
                  </body>
                </body>
              </body>
            </body>
          </body>
        </body>

        <body name="l2_ankle_Servo" pos="{ankle_servo_x} {ankle_servo_y}
{ankle_servo_z}">
          <geom mass="0.01" type="box" size="{servo_length} {servo_width}
{servo_height}" pos="0 0 0" rgba="0 0 1 1"/>

          <body name="l2_ankle_horn" pos="{servo_length} {servo_horn_pos} 0"
axisangle="0 1 0 -90">
            <joint name="j2_as_horn" type="hinge" axis="0 1 0" pos="0 0 0" damping="0"
stiffness="0"/>
            <geom mass="0.001" type="box" size="{horn_length} {horn_width}
{horn_height}" pos="{servo_horn_x} 0 0" rgba="1 1 1 1"/>

            <body name="l2_as_rod" pos="{as_rod_b} 0 0" axisangle="0 1 0 90">
              <joint name="j2_as_rod" type="hinge" axis="0 1 0" damping="0"
stiffness="0.3"/>
              <geom mass="0.0001" type="box" size="{as_rod} .1 .1" pos="{as_rod_pos} 1
```

```
0" contype="1" rgba="1 1 0 1"/>

                    <body name="l2_as_1" pos="{as_1_b} 0 0" axisangle="0 1 0 90">
                        <joint name="j2_as_1" type="ball" damping="0"/>
                        <geom mass="0.001" type="box" size="{as_1} {bar_width} .0005"
 pos="{as_1_pos} {bar_width} 0" contype="0" rgba="1 0 0 0"/>

                    </body>
                  </body>
                </body>
              </body>

            </body>

        </body>

    </worldbody>

    <equality>
        <weld name="l1_4bar_1" active="true" body1="l1" body2="l1_b1_4"
relpose="-{weld_b1_pos} 0 0 1 0 0 0"/>
        <weld name="l1_4bar_2" active="true" body1="l1_b1_3" body2="l1_b2_4"
relpose="{weld_b2_pos} 0 0 0 0 1 0"/>
        <weld name="l1_t" active="true" body1="l1_b2_1" body2="l1_t_3"
relpose="{weld_t_pos} 0 0 0 0 1 0"/>

0"/> <weld name="l1_ks" active="true" body1="l1_ks_6" body2="l1_t_2" relpose="0 0 0 1 0 0
```

```
1 0"/><weld name="l1_as" active="true" body1="l1_b1_1" body2="l1_as_1" relpose=".7 0 .1 0 0

        <weld name="l2_4bar_1" active="true" body1="l2" body2="l2_b1_4"
relpose="-{weld_b1_pos} 0 0 1 0 0 0"/>
        <weld name="l2_4bar_2" active="true" body1="l2_b1_3" body2="l2_b2_4"
relpose="{weld_b2_pos} 0 0 0 0 1 0"/>
        <weld name="l2_t" active="true" body1="l2_b2_1" body2="l2_t_3"
relpose="{weld_t_pos} 0 0 0 0 1 0"/>

        <weld name="l2_ks" active="true" body1="l2_ks_6" body2="l2_t_2" relpose="0 0 0 1 0 0
0"/>
        <weld name="l2_as" active="true" body1="l2_b1_1" body2="l2_as_1" relpose=".7 0 0.1 1
 0 0 0"/>



    </equality>

    <actuator>
        <position name="servo_1" joint="j1_ks_horn" kp="100"/>
        <position name="servo_2" joint="j1_as_horn" kp="100"/>

        <position name="servo_3" joint="j2_ks_horn" kp="100"/>
        <position name="servo_4" joint="j2_as_horn" kp="100"/>
    </actuator>

</mujoco>
```

"""

Metric Selection: Choose "Overall Distance Traveled in a Particular Direction" as the performance metric. This metric effectively measures the robot's ability to move consistently towards a set goal or target over time.

```
7]  ✓ 0.0s

Velocity of the configuration leg_0g is 0.58 inches/min
Velocity of the configuration leg_10g is 0.60 inches/min
Velocity of the configuration leg_20g is 0.57 inches/min
Velocity of the configuration leg_30g is 0.68 inches/min
```

Data Collection

Data Acquisition: Utilize the MuJoCo simulation environment to log detailed positional data of the robot. Ensure that data collection captures every movement of the robot within the simulation environment to provide a comprehensive dataset for analysis.

Data Parameters: Specifically, focus on the 'x' coordinate if you are measuring displacement along the x-axis. Record the positional x values at regular time intervals to analyze the movement pattern and speed.

Data Analysis

Displacement Calculation: Calculate the displacement by measuring the change in the 'x' coordinate over the selected time frame. Displacement can be calculated using the formula:

Displacement = x(t2) - x(t1)

Where $x(t1)$ and $x(t2)$ are the x positions at the beginning and end of the time frame, respectively.

Speed Calculation: Compute the average speed of the robot along the x-axis using the displacement data and the total time elapsed. The speed can be calculated with:

Speed = Displacement / Total Time

This calculation provides insight into how quickly the robot is able to cover distance in the simulation, which is critical for tasks requiring time efficiency.

Performance Evaluation

Trend Analysis: Analyze the trends in the displacement data over multiple runs or simulations to assess consistency, reliability, and any potential issues with robot control algorithms.

Performance Benchmarks: Compare the calculated speed and displacement against predefined performance benchmarks or requirements to evaluate the robot's efficiency and effectiveness in achieving its motion goals.

Visualization and Reporting

Data Visualization: Use graphs to plot the x displacement over time, which can help in visually assessing the robot’s performance, detecting any deviations, or identifying periods of maximum efficiency.

Report Generation: Summarize the findings in a detailed report, highlighting key performance metrics, data analysis insights, and recommendations for improvements based on the simulation data.

• Add / elements as needed to track any additional variables necessary for computing robot performance. This isn’t necessary for joint position / speed variables, which use the methods for accessing them. qpos() or qvel()

• Create a relatively granular sweep of your performance metric over the range of design variable(s) and plot your results.

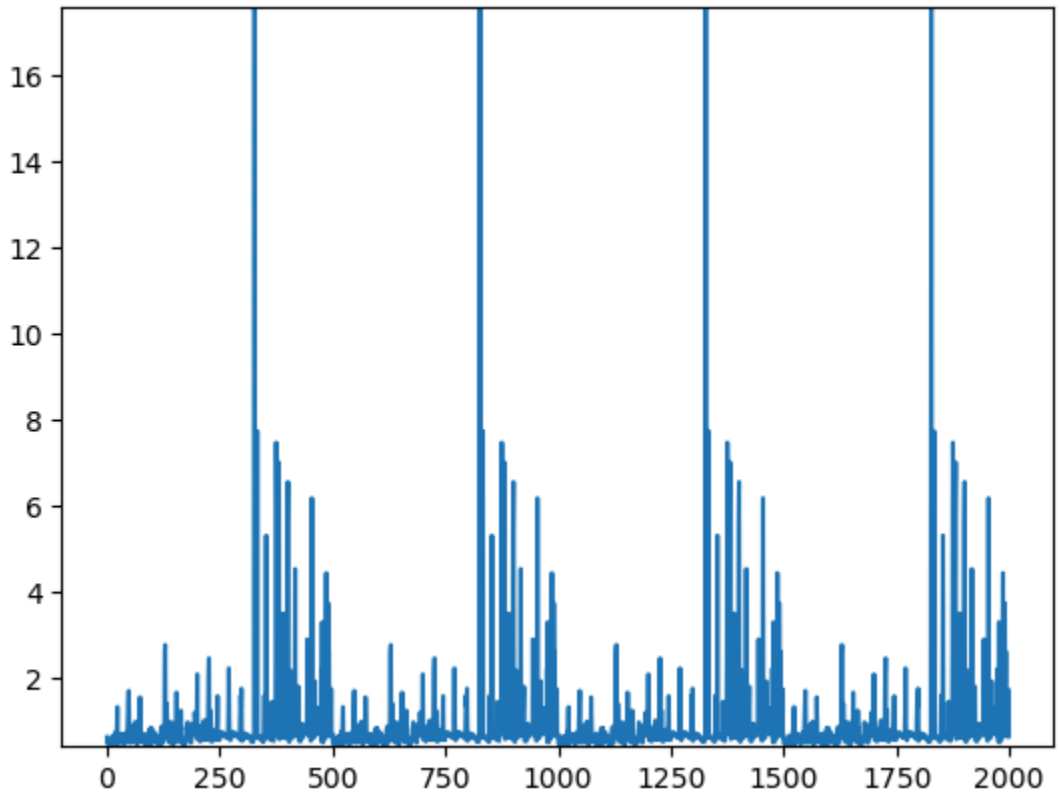


Figure 5: X-Label: Index of generated parameters

Y-Label: Maximum distance based on those parameters

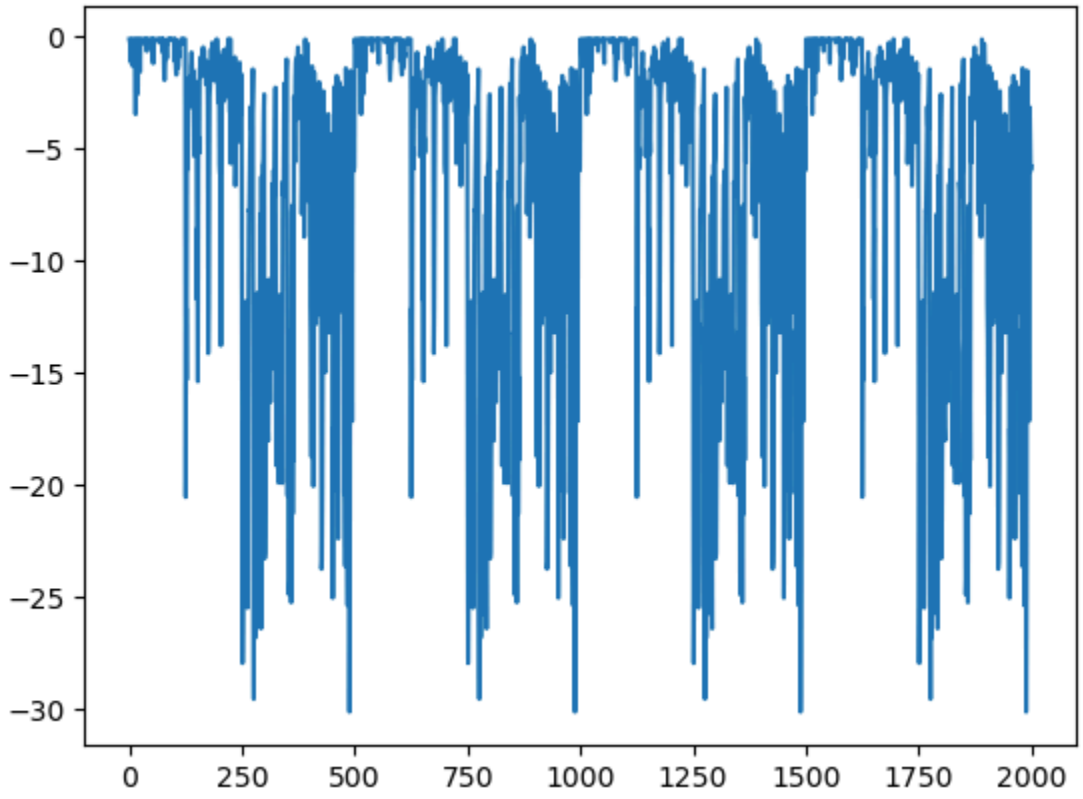


Figure 6: X-Label: Index of generated parameters

Y-Label: Minimum distance based on those parameters

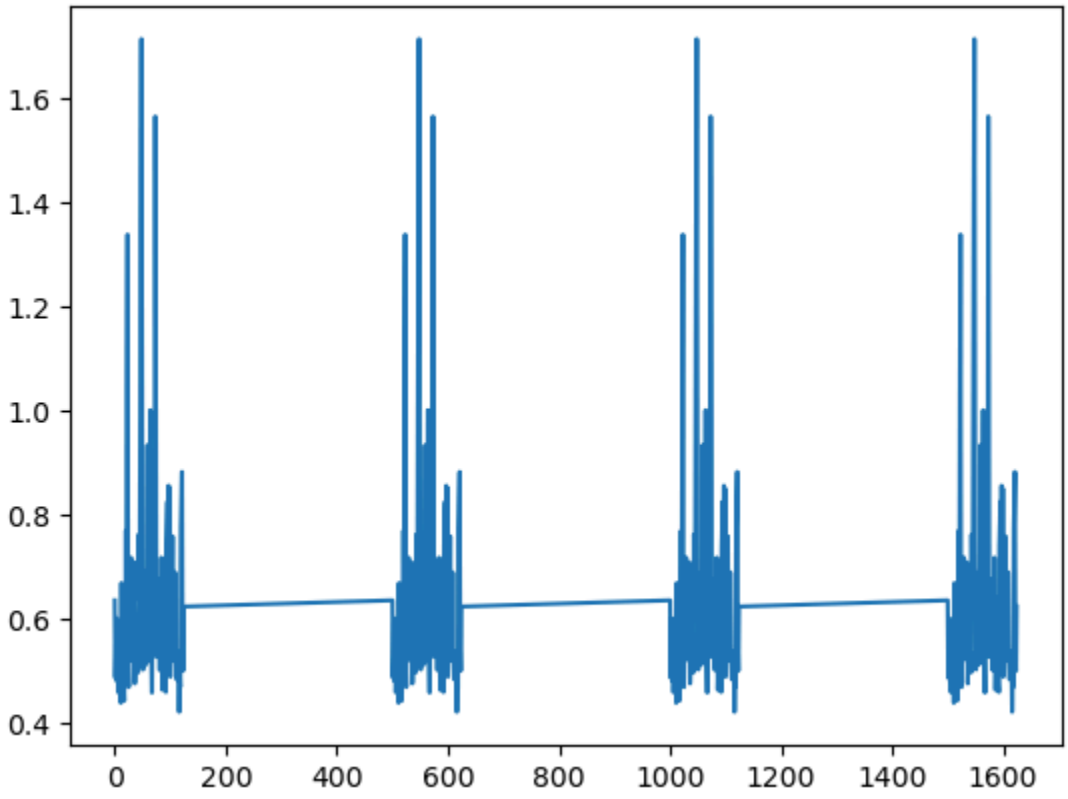


Figure 7: X-Label: Index of generated parameters(Filtered Out where the frequency of the servo was 5.5)

Y-Label :Maximum distance based on those parameters(Filtered Out where the frequency of the servo was 5.5)

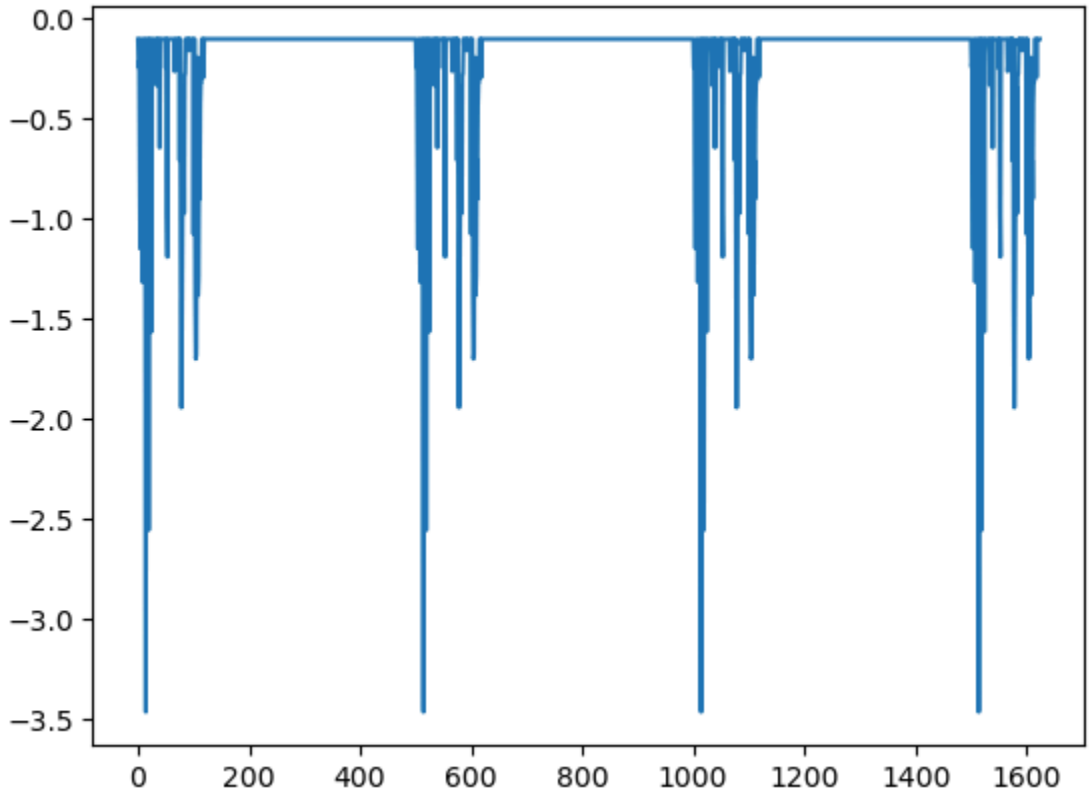


Figure-8: X- Label:Index of generated parameters(Filtered Out where the frequency of the servo was 5.5)

Y-Label: Minimum distance based on those parameters (Filtered Out where the frequency of the servo was 5.5)

Performance Variation in Prototype

1. Varying the Metric: In the real-life prototype, vary the 'x' positional value by modifying factors such as initial speed, acceleration, or introducing obstacles or gradients in the robot's path. Monitor how these changes affect the overall distance traveled in a particular direction.

Comparison of Simulation and Real-Life Results

2. Qualitative Analysis: Observationally, the robot in the real-life setup may demonstrate less predictable behavior than in the MuJoCo simulation due to unforeseen environmental interactions or mechanical wear and tear.
3. Quantitative Analysis: Measure the displacement and speed in the real-life tests under similar conditions as the simulation. Record these values to compare directly with the simulation data, noting any significant variances in performance metrics.

Attributing Differences

4. Modeled vs. Unmodeled Factors: Attribute any discrepancies between the simulation and real-world performance to factors such as:
    - Friction: Real-world friction coefficients may differ significantly from those modeled in the simulation.
    - Sensor Noise and Accuracy: Real-life sensors might introduce noise and data inaccuracies not present in the simulated environment.
    - Mechanical Imperfections: Wear and tear or manufacturing imperfections affecting the robot's movement efficiency.

Implementation of Real-Life Experimentation

5. Experimental Setup: To validate the simulation results, replicate the environmental conditions and robot configurations used in MuJoCo as closely as possible in the physical prototype testing.
6. Data Collection Consistency: Use the same sampling rates for data collection and ensure the sensors and measurement tools are calibrated similarly to those used in the simulation settings.

Streamlining the Experimentation Process

7. Automation of Data Collection: Implement automated tools and scripts to start and stop experiments at predefined times or conditions, and to log data automatically.
8. Controlled Environment: Conduct tests in a controlled environment where variables like temperature, lighting, and surface material are kept constant to reduce the influence of external factors.
9. Iterative Testing: Develop a schedule for systematic testing where only one variable is changed at a time, allowing for clear identification of how each factor specifically influences the robot's performance.

Plan and Execute the Manufacturing

Our team used the Five-Layer Design to create our legs for the robot. To do this we used LibreCAD to create the DXF file. In figure our DXF file shows how the legs are made up of nine joints (the blue lines), eighteen bridges (the yellow lines), one hole (the green box), and one cut (the cyan box) all within the body shape (the red lines) the forms a rectangle with a smaller rectangle on the side.

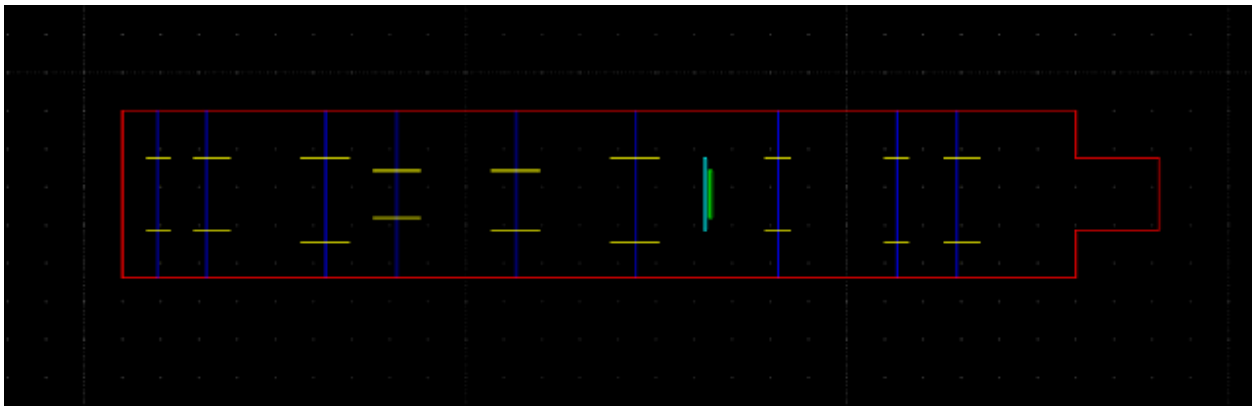


Fig.9 : DXF file of the leg in LibreCAD

This smaller rectangle will fit inside the hole; this will create the first four-bar mechanism in the leg. During the design of the DXF files the cut and hole got switched, this was noticed in the final cut when the smaller rectangle did not perfectly fit through the hole. A quick fix for this problem was shaving down the smaller rectangle and physically cutting the hole to be a bit bigger. The rest of the joints and links were then folded to create the final four-bar linkage with a knee joint included. Our team was advised to add this knee joint/extra link to have a better lift on the foot when the robot moved.

Before cutting with the DXF files on the laser cutter, our team created a prototype with this design in mind. We used poster board, duct tape, and note cards to build this prototype as seen in figure 10 . This prototype worked and made the movements we desired for our robot.

Fig.10: Prototype of the DXF file

With our research focusing on the ostrich leg, we wanted to create a leg made up of two four-bar linkage. In figure enter it shows the progress that we have made with our designs. In the first prototype, it was able to have the link stiffness that we wanted, however, it did not generate the range of movement we desired. This prototype was made with two layers of cardstock and masking tape. In the second prototype ,we only used one layer of cardstock and made the links bigger. This change created the range of movement we wanted and we discovered that mounting the ankle motor created a large moment of force on the knee motor. For the final prototyp,e we were advised to create another link that would be where the knee joint would attach to the motor. This allows for the motor to work with the first four-bar linkage motor and helps with the robot's ability to walk.

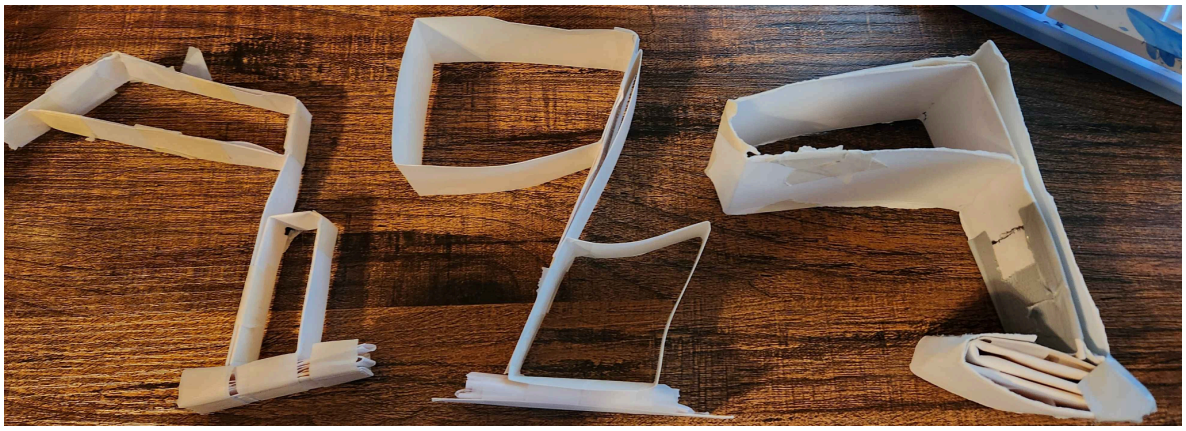


Fig.11 : The first three prototypes: Left is the first, the middle is the second and the right is the final prototype before using the laser cutter

The code we used to create all the DXF files is similar to the one in the book [1]. Below is the code that shows the images of the layers it generates. This code is called makingthelayers.ipynb and will be attached to with this paper.

In [1]:
```
import foldable_robotics.dxf as frd
import foldable_robotics as fr
import foldable_robotics.manufacturing as frm
from foldable_robotics.layer import Layer
from foldable_robotics.laminate import Laminate
import foldable_robotics.parts.castellated_hinge2 as frc
import shapely.geometry as sg
from foldable_robotics.pdf import Page
import foldable_robotics.pdf as frp
import socket
import foldable_robotics.parts.pill_joint as frpill
import foldable_robotics.plotter_support as frplt
```

In [2]:
```
fr.display_height=300
fr.resolution = 4
desired_degrees = 120
thickness = 1
plain_width = frm.plain_hinge_width(desired_degrees,thickness)
plain_width
```

Out[2]:
```
1.7320508075688774
```

All of this is from the given code example

In [3]:
```
support_width = 2 # must be larger than hinge width
kerf = .05
is_adhesive = [False,True,False,True,False]
arc_approx = 10
NUM_LAYERS = 5
bridge_thickness = 2
bounding_box_padding = 10
jig_spacing = 10
jig_dia = 5
```

As is this code above.

In [4]:
```
body_vertices = frd.read_lwpolylines('ostrichlegforreal.dxf', layer='body',arc_appr
body_vertices
```

Out[4]:
```
[[[50.00940537840764, 368.0045980266],
  [93.40940537840761, 368.0045980266],
  [93.4094053784076, 120.0045980266],
  [81.00940537840762, 120.0045980266],
  [81.00940537840762, 98.30459802659999],
  [62.4094053784076, 98.30459802659999],
  [62.4094053784076, 120.0045980266],
  [50.0, 120.0],
  [50.00940537840764, 368.0045980266]]]
```

From the drawing file of the dxf we are able to create the body_vertices. This is also like the example

In [5]:
```
body_polygons = [sg.Polygon(item) for item in body_vertices]
body_polygons[0]
```

Out[5]:

In [6]:
```
body_layer = Layer(*body_polygons)
body_layer
```

Out[6]:

Creates the layer.

In [7]:
```
hole_vertices = frd.read_lwpolylines('ostrichlegforreal.dxf',layer='holes',arc_appr
hole_layer = Layer(*[sg.Polygon(item) for item in hole_vertices])
hole_layer
```

Out[7]:

Creates the holes on the layer.

In [8]:
```
body_layer -= hole_layer
body_layer
```

Out[8]:

In [9]:
```
cut_vertices = frd.read_lwpolylines('ostrichleg.dxf',layer='cuts', arc_approx = arc
cut_layer = Layer(*[sg.LineString(item) for item in cut_vertices])
cut_layer
cut_layer <<=.5
cut_layer
body_layer -= cut_layer
body_layer
```

Out[9]:

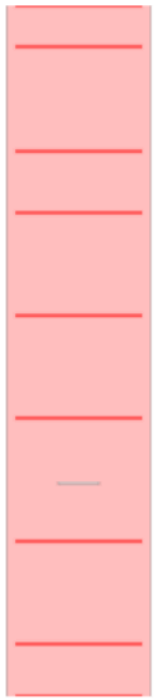
In [10]:
```
joint_vertices = frd.read_lwpolylines('ostrichlegforreal.dxf',layer='joints',arc_ap
l = sg.LineString(joint_vertices[0])
l
```

Out[10]:

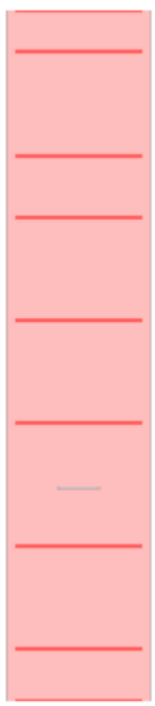
In [11]:
```
joint_lines_original_layer = Layer(*[sg.LineString(item) for item in joint_vertices
joint_lines_original_layer
```

Out[11]:

In [12]:
```
body_layer.plot()
joint_lines_original_layer.plot()
```



In [13]:
```
joint_lines_modified_layer = joint_lines_original_layer & body_layer
body_layer.plot()
joint_lines_modified_layer.plot()
```



In [14]:
```
modified_joint_vertices = [list(item.coords) for item in joint_lines_modified_layer
modified_joint_vertices
```

```
Out[14]: [[(53.1094053784076, 346.3045980266), (90.30940537840759, 346.3045980266)],
          [(53.1094053784076, 358.7045980266), (90.30940537840759, 358.7045980266)],
          [(53.1094053784076, 315.3045980266), (90.30940537840759, 315.3045980266)],
          [(53.1094053784076, 296.7045980266), (90.30940537840759, 296.7045980266)],
          [(53.1094053784076, 265.7045980266), (90.30940537840759, 265.7045980266)],
          [(53.10940537840759, 234.7045980266), (90.30940537840759, 234.7045980266)],
          [(53.10940537840759, 197.5045980266), (90.30940537840758, 197.5045980266)],
          [(53.10940537840759, 166.5045980266), (90.30940537840758, 166.5045980266)],
          [(53.10940537840759, 151.0045980266), (90.30940537840758, 151.0045980266)]]
```

```
In [15]: simple_joint_layer = joint_lines_modified_layer << plain_width/2
         simple_joint_layer
```

Out[15]:

```
In [16]: hole,dummy = frm.calc_hole(modified_joint_vertices,plain_width/2)
         fr.my_line_width=0
         holes = hole.to_laminate(NUM_LAYERS)
         holes<<=.5
         holes
```

Out[16]:

```
<Figure size 640x480 with 0 Axes>
```

```
In [17]: rigid_layer = (body_layer - simple_joint_layer)
         rigid_layer
```

Out[17]:

In [18]:
```
adhesive_layer = rigid_layer & body_layer
adhesive_layer
```

Out[18]:

In [19]:
```
ideal_final_device = Laminate(rigid_layer,adhesive_layer, body_layer,
adhesive_layer,rigid_layer)
ideal_final_device
```

Out[19]:

Creates the adhesive layer.

In [20]:
```
ideal_final_device[0]
```

Out[20]:

In [21]:
```
ideal_final_device[2]
```

Out[21]:

In [28]:

```
actual_final_device = ideal_final_device- holes - removal
actual_final_device
```

Out[28]:

In [29]:

```
keepout = frm.keepout_laser(actual_final_device)
keepout
```

Out[29]:

In [30]:

```
layer_id = frm.build_layer_numbers(NUM_LAYERS,
text_size=jig_dia)
layer_id = layer_id.simplify(.2)
layer_id[0]
```

Out[30]:

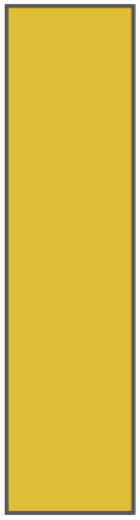
In [31]:

```
(x1,y1),(x2,y2) = actual_final_device.bounding_box_coords()
w1,h1 = actual_final_device.get_dimensions()
w2 = round(w1/jig_spacing)*jig_spacing+jig_spacing+support_width
h2 = round(h1/jig_spacing)*jig_spacing+jig_spacing+support_width
x1 -= (w2-w1)/2
y1 -= (h2-h1)/2
x2 += (w2-w1)/2
y2 += (h2-h1)/2
points = []
points.append(sg.Point(x1,y1))
points.append(sg.Point(x2,y1))
points.append(sg.Point(x1,y2))
points.append(sg.Point(x2,y2))
alignment_holes_layer = Layer(*points)
alignment_holes_layer<<=(jig_dia/2)
alignment_holes=alignment_holes_layer.to_laminate(NUM_LAYERS)
alignment_holes
```

Out[31]:

In [32]:
```
sheet_layer = (alignment_holes_layer<<bounding_box_padding).bounding_box()
sheet=sheet_layer.to_laminate(NUM_LAYERS)
sheet
```

Out[32]:



In [33]:
```
removable_scrap = frm.calculate_removable_scrap(
actual_final_device,sheet,support_width,is_adhesive)
web = removable_scrap-alignment_holes-layer_id.translate(x1+jig_dia,y1-jig_dia/2)
web
```

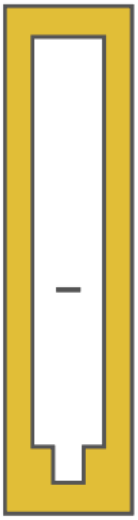
Out[33]:

In [34]:
```
(web|actual_final_device)
```

Out[34]:

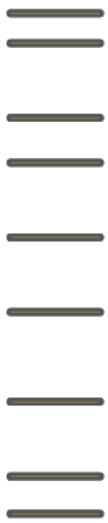
In [35]:
```
second_pass_scrap = sheet-keepout
second_pass_scrap
```

Out[35]:



In [36]:
```
first_pass_scrap = sheet - second_pass_scrap - actual_final_device
first_pass_scrap = frm.cleanup(first_pass_scrap,.00001)
first_pass_scrap
```

Out[36]:



In [37]:
```
support = frm.support(actual_final_device,frm.keepout_laser,support_width,support_w
support
```

Out[37]:

In [38]:
```
support | bridges_lam
```

Out[38]:

In [39]:
```
supported_design = web|actual_final_device|support| bridges_lam
supported_design
```

Out[39]:

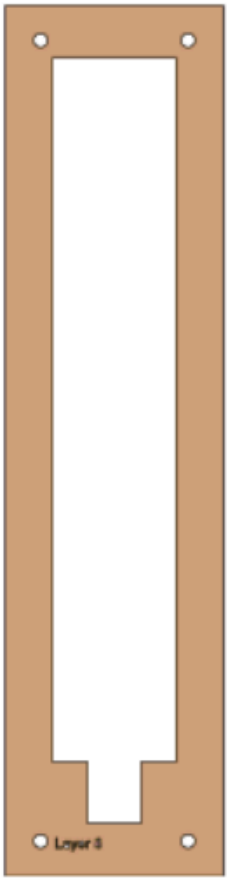
In [40]:
```
cut_material = (keepout<<kerf)-keepout
cut_material
```

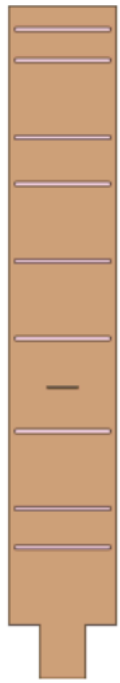
Out[40]:

In [41]:
```
remaining_material = supported_design-cut_material
remaining_material
```

Out[41]:

In [42]:
```
remaining_parts = frm.find_connected(remaining_material,is_adhesive)
for item in remaining_parts:
    item.plot(new=True)
```


Layer 3

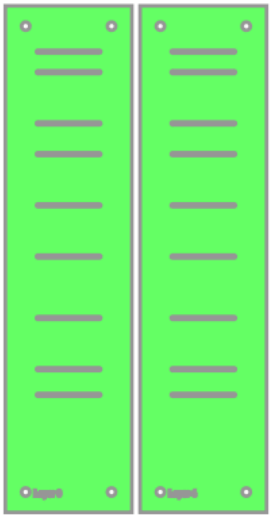


In [43]:
```
test_part=actual_final_device>>1
for result in remaining_parts:
    if not (result&test_part).is_null():
        break
result
```

Out[43]:

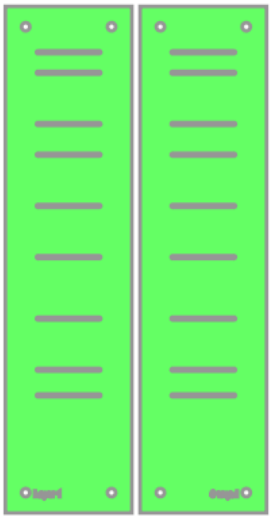
In [44]:
```
w,h = supported_design.get_dimensions()
p0,p1 = supported_design.bounding_box_coords()
rigid_layer = supported_design[0] | (supported_design[-1].translate(w+5,0))
rigid_layer
```

Out[44]:



In [45]:
```
l4 = supported_design[3].scale(-1,1)
p2,p3 = l4.bounding_box_coords()
l4 = l4.translate(p0[0]-p2[0]+w+5,p0[1]-p2[1])
adhesive_layer = supported_design[1] | l4
adhesive_layer
```

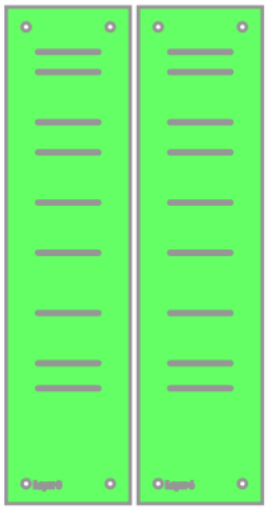
Out[45]:



In [46]:
```
first_pass = Laminate(rigid_layer,adhesive_layer,supported_design[2])
first_pass.export_dxf('first_pass')
```

In [47]:
```
first_pass[0]
```

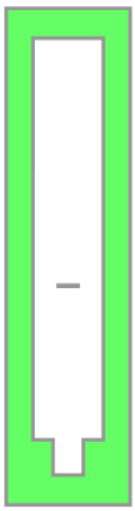
Out[47]:



In [48]:

```
final_cut = sheet - keepout
final_cut = final_cut[0]
final_cut.export_dxf('final_cut')
final_cut
```

Out[48]:



Once our team was able to generate the DXF files of the first pass0, first pass1, first pass2, and final cut, we attempted to use a vinyl cutter to cut the layers. However, we were able to obtain a universal small laser after cutting the first layers of our rigid material. After cutting the adhesive layer and the joint layer with the laser, our team discovered that the vinyl cutter versus the laser cutter was slightly off in alignment. We proceeded to recut our rigid material with the laser so that it would be easier to combine the layers in the lamination process. The lamination process went smoothly by following the instructions in our class's textbook, and after this, we were then able to complete the final cut of the robot to get our rectangle and smaller rectangle shape.

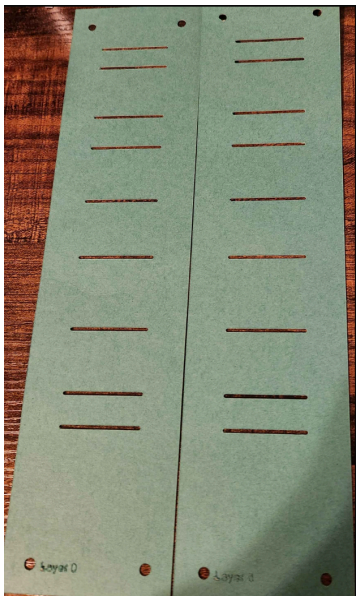


Fig.12 : Rigid layer cut with the vinyl cutter

The next step was to create the body of the robot. This was done by using balsa wood for the base of the body, ball bearings, wooden sticks, and hot glue. The balsa wood was used as the platform that would hold the breadboard and motors, while the ball bearings and wooden sticks were used to create the balanced legs of the back end of the robot. We wanted to have wheels so that the robot would not have to work harder to move with more friction generated from wooden support posts.

When it came to motor placement we had to go through many different prototypes to see what would work to get the small four bar to move properly. In the first iteration of the final design the motor is what connected the legs to the platform. Fishing wires were connected to the back motors to the knee link. This caused the robot's foot (the link that makes contact with the ground) to lift up. The left-side motors will run at the same time and then the right-side motors will run at the same time, this will cause the legs to move out of sync and walk forward. However the small four bar linkage did not move correctly. The next idea was to move the motor behind the small four bar cause it to push. However the horn was unable to reach the four bar. The team then tried to attach fishing wire onto the top of the small four bar, since that idea was working for the bigger four bar. This also did not work, because it did not create the push we needed for the robot to move. The last and final idea that we use was to create a bar and attach it on to the horn. This bar was made of wire and hotglue and did create the push we needed to get the robot to move.

Another change that was made was to add another ball bearing the front of the body. This ball bearing helped with the weight of the robot and kept it leveled instead of angling down.

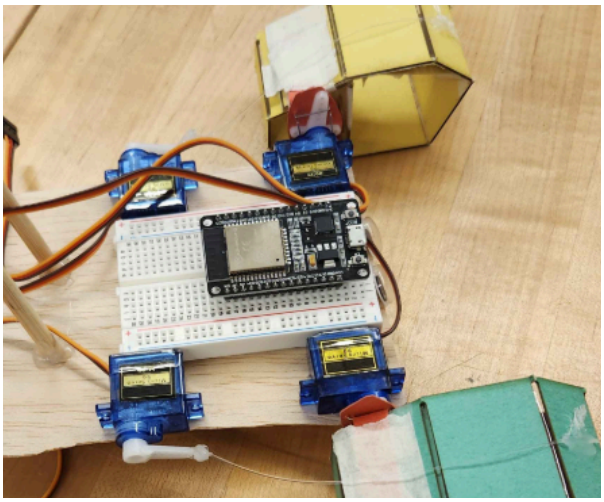


Fig.13 : Showing the placement of the motors and how they connect to the legs in the first iteration

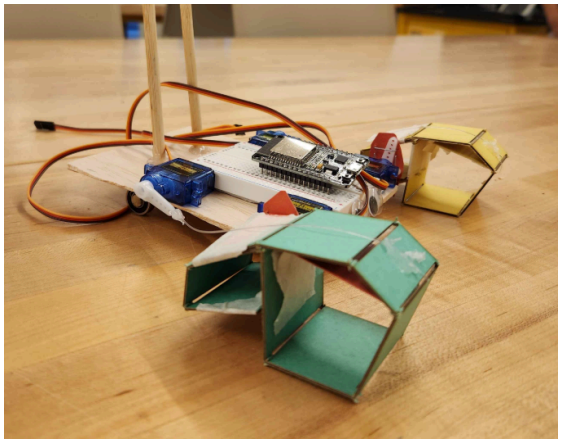


Fig.14 : Side view of the robot before wires are connected

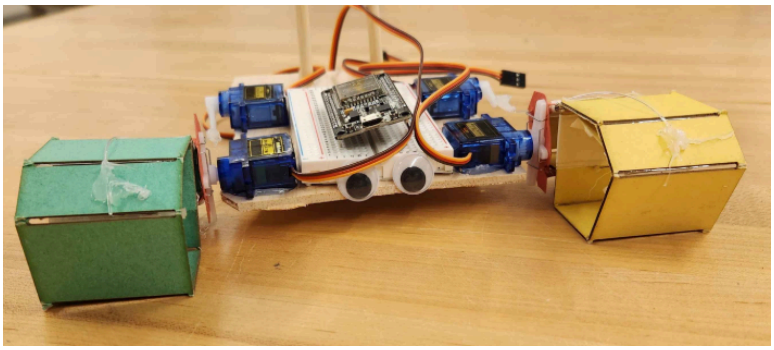


Fig.15 : Front view of the robot before wires are connected

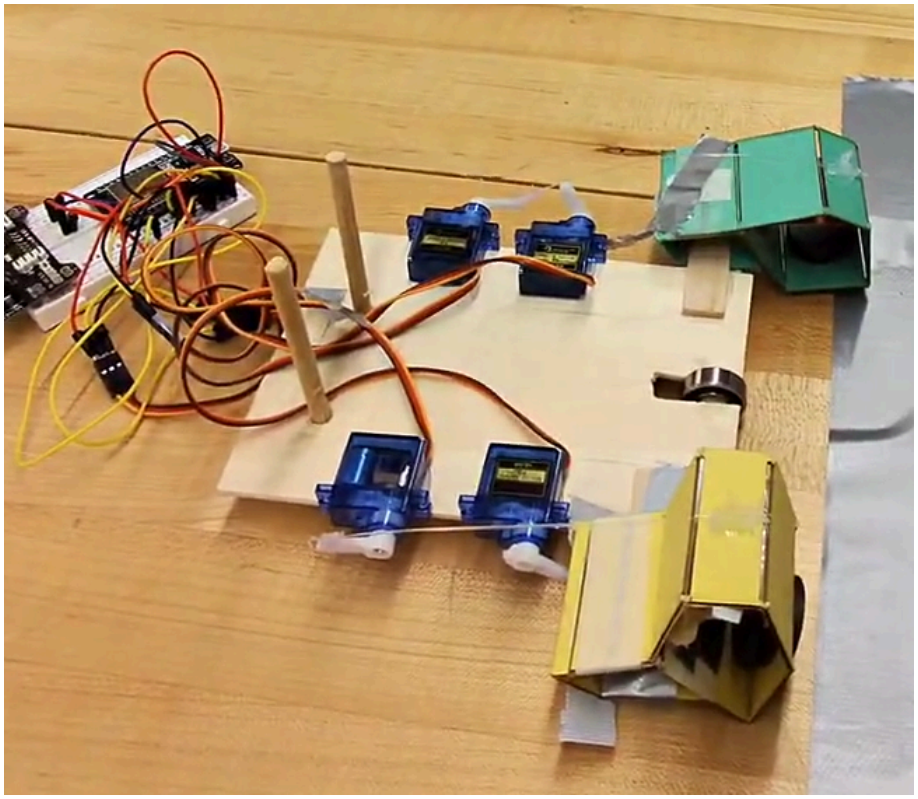


Fig.16 : Final look for the robot with the use of the rods

Experimental Validation and Analysis

Experimental setup

For the experimental setup, the ostrich was placed on a table with tape and ruler visual reference. The circuit was positioned behind the ostrich to minimize its load. It was powered by a DC power supply operating at 12 V. The experimental setup is shown in the Figure 17.

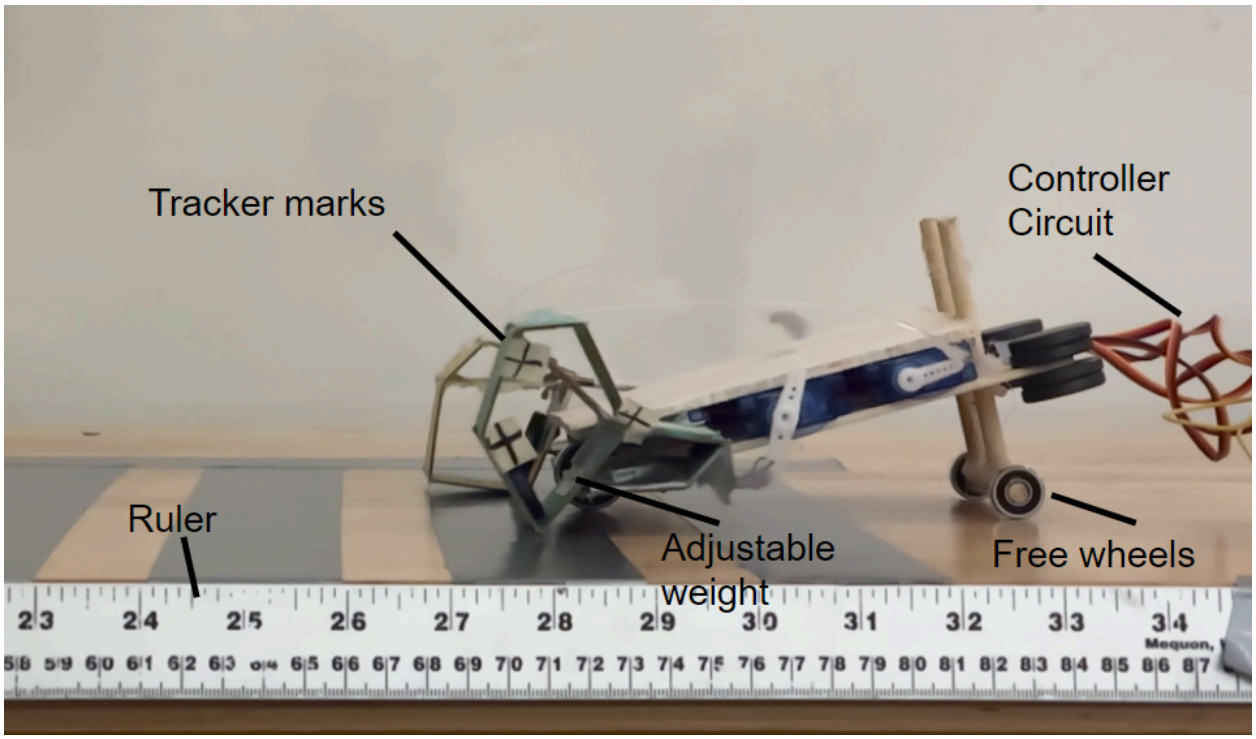


Fig.17 : Experimental setup

Design Parameter

The primary design parameter tested was the force at which the feet attach to the ground. Increased weight on the feet is predicted to alter both the speed and stability of the feet. To evaluate this, additional mass was added to the feet in increments of 10 g per leg. The added mass was secured using magnets.

The motion was generated by a cosine wave. The following parameters were kept constant during testing:

- Frequency: 0.5 Hz
- Amplitude: 60
- Phase difference: 90 degrees

Data Collection

For data collection, the image tracking software Tracker was used to measure and monitor the movement of the double four-bar mechanism. Three tracking markers were placed on the four-bar linkage, as shown in figure 18.

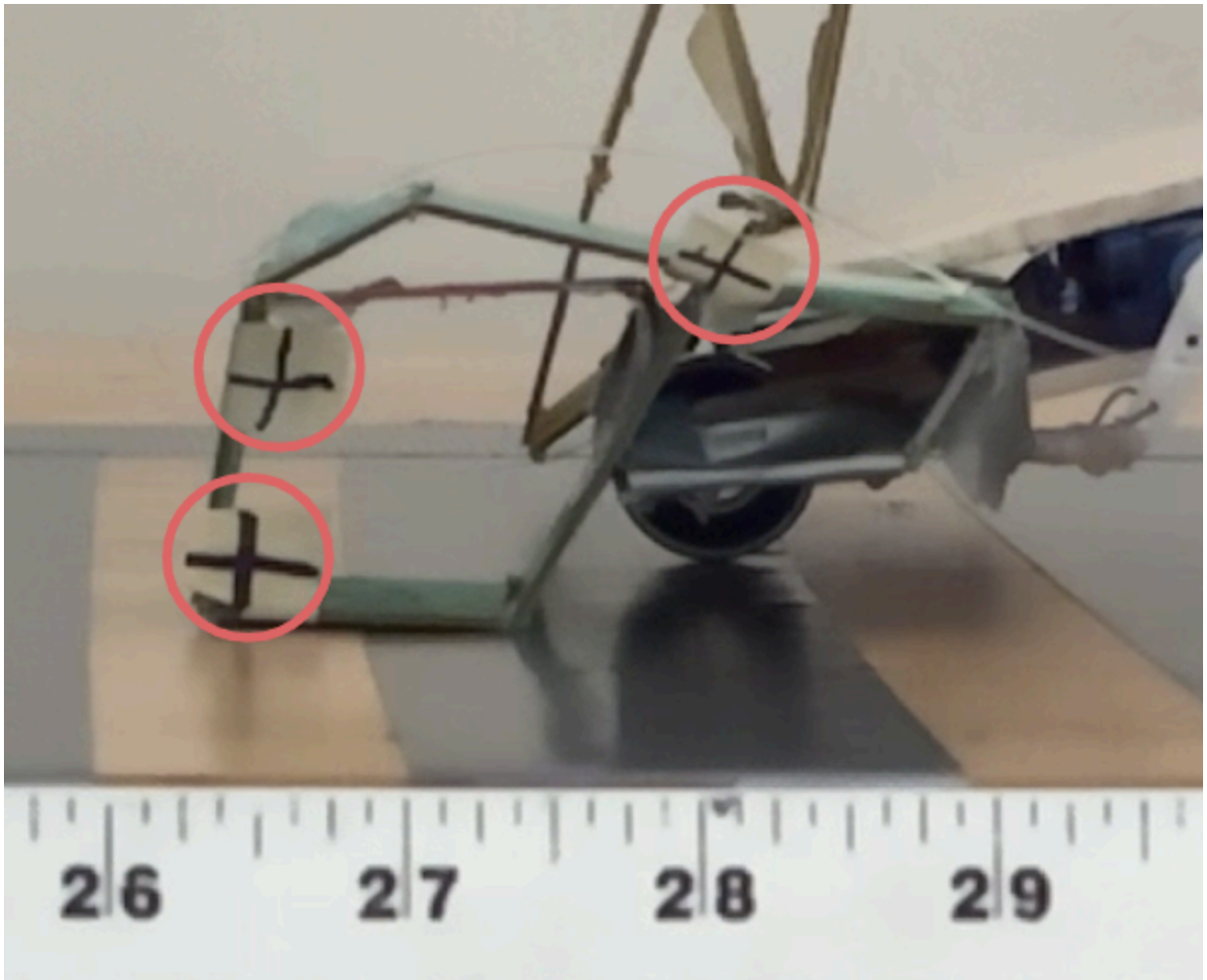


Fig.18 : Tracker markers (circled)

Using the image tracking software Tracker, we analyzed the movement of the designated markers over a duration of 30 seconds for each configuration.

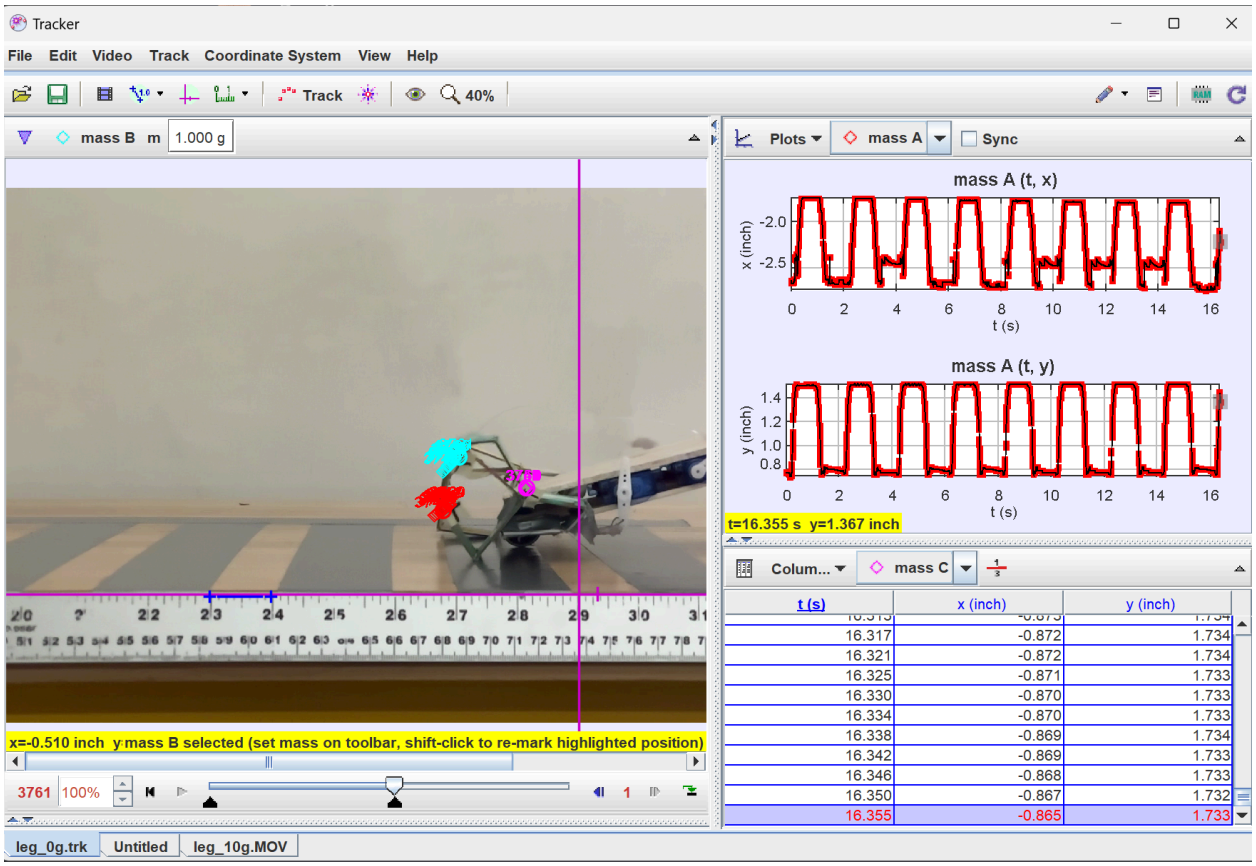


Fig.19 : Tracker application setup

The collected data was exported as a CSV file and imported into a Jupyter Notebook for analysis. For comparison, simulation data was compared against tracked data.

Model Analysis

Translation of motion

The physical model was compared against the cosine way generating motion against its motion. Both the knee and ankle were compared for this analysis. As Figure 20 shows, the motion generated by the cosine way is translated without loss to the knee and ankle four bar linkage.

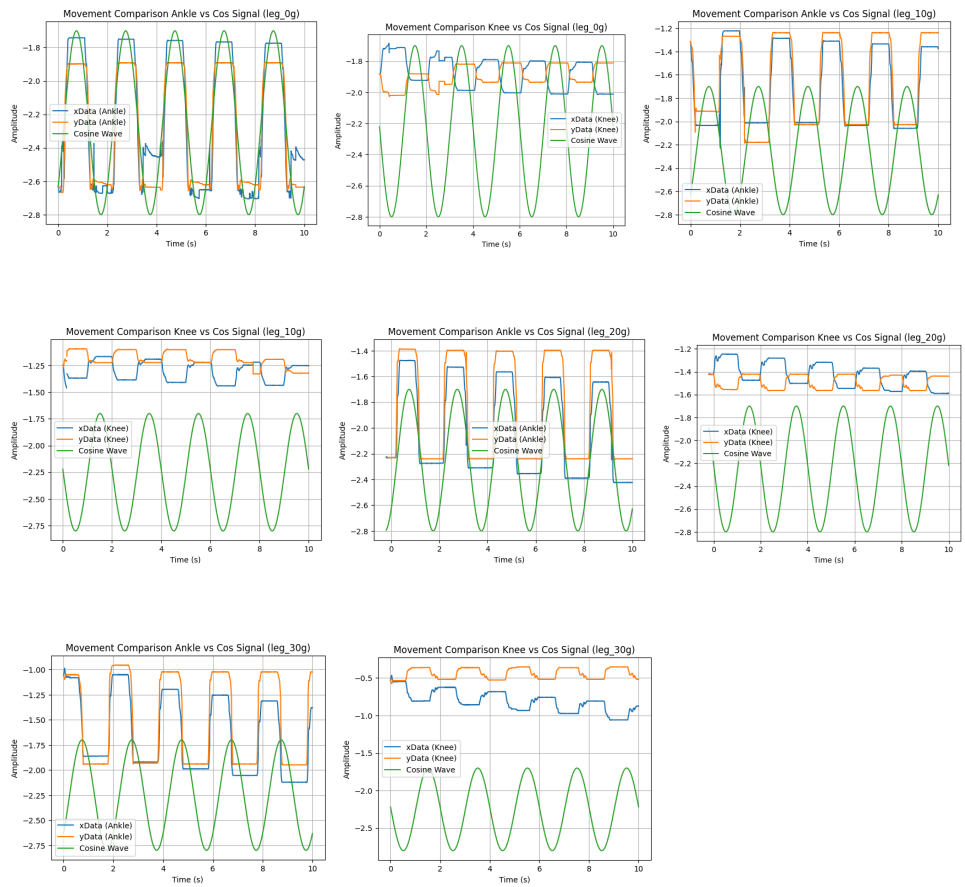


Fig.20 : Knee and ankle comparisons to the cosine wave

Stability of the linkage

Based on the data shown in Figure 33, it is validated that increasing the weight on the ankle stabilizes the design. This finding is also supported by the simulation results mentioned in the previous section.

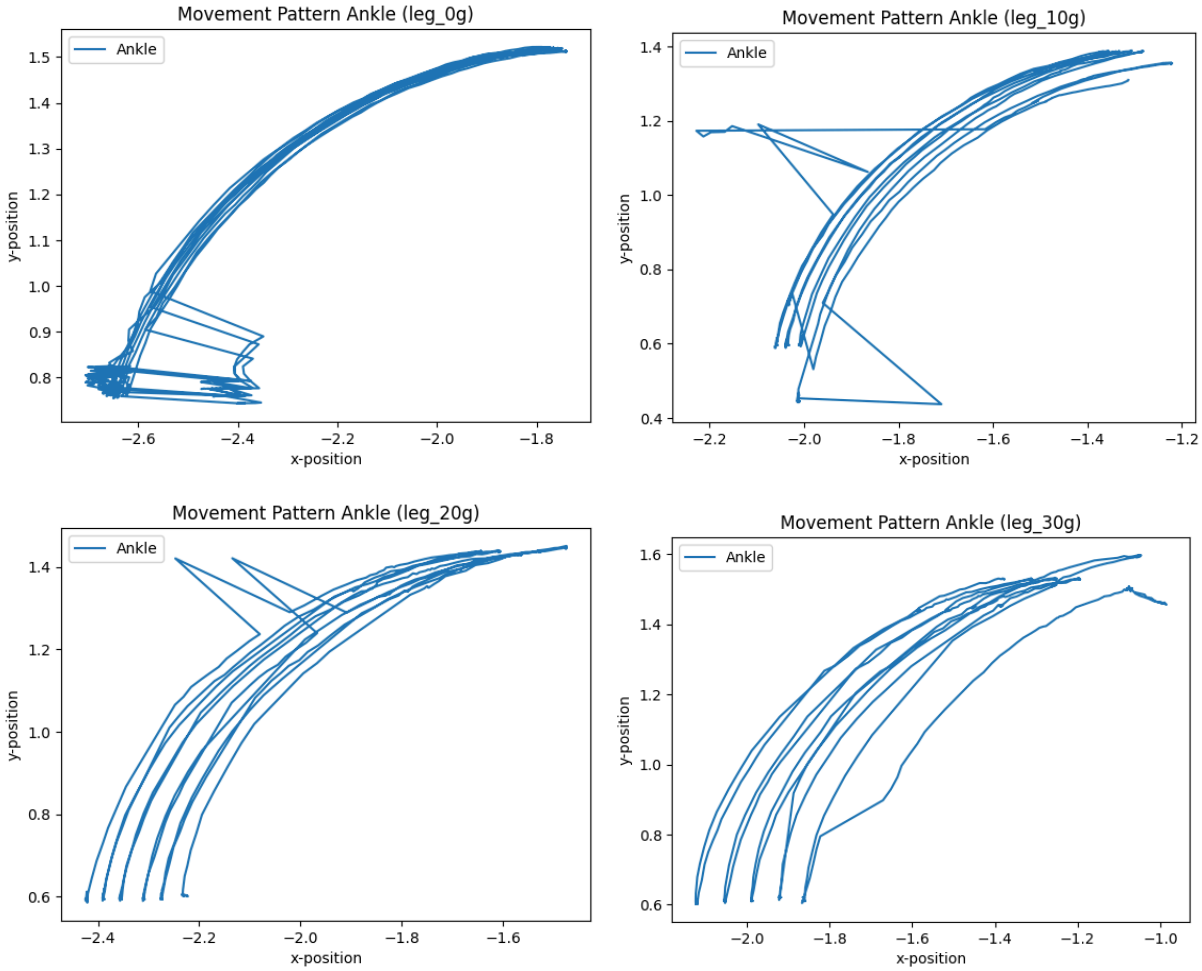
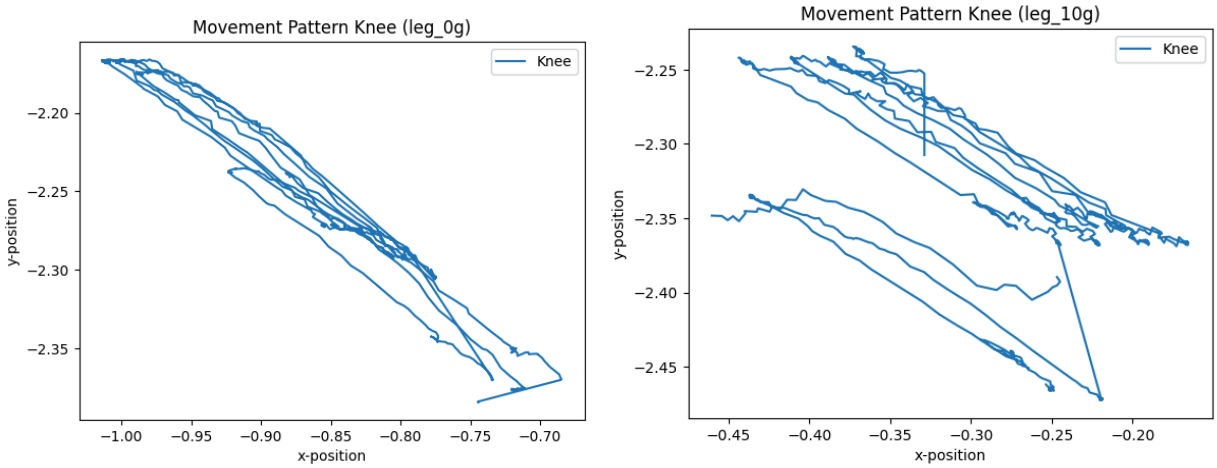


Fig.21 : Ankle motion



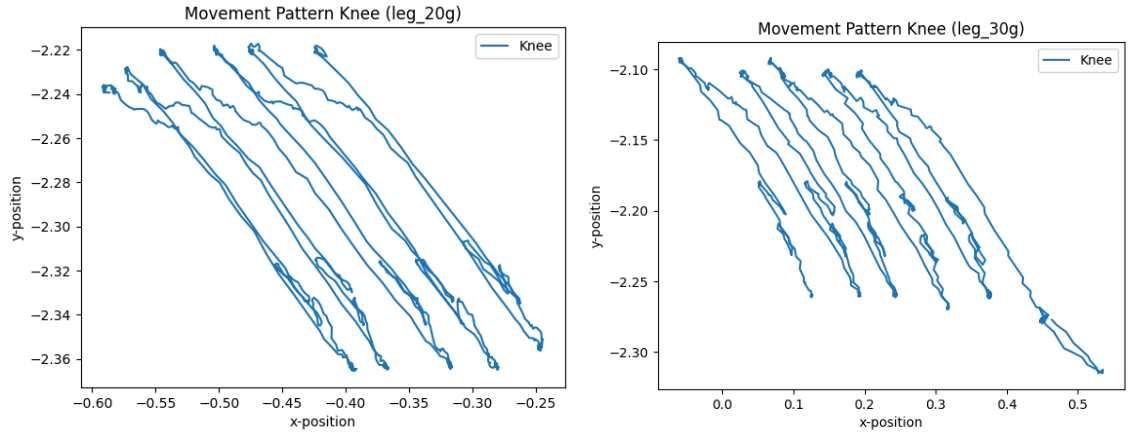


Fig.22 : Knee motion

Increased Velocity

With increased weight, it was observed that the speed of the ostrich model increased, thereby satisfying the test criteria.

One limitation encountered was that adding additional mass caused the servo to stall due to the excessive load. This issue can be addressed in future designs by utilizing servos with higher capacity.

Velocity of the manufactured configuration 0g is 0.603765 inches/min

Velocity of the simulated configuration 0g is 0.8115001824000001 inches/min

The movement is visualized in 25. Overall error between simulated and real model is ~25%

These findings are also validated by the simulation results, as shown in figure:

Table .1 : ankle weight vs velocity relations

Additional ankle weight (grams)	**Velocity (incles/min)**
0	0.58

10	0.6
20	0.57
30	0.68

Walk through of our code

```
import os
import math
import mujoco
import numpy as np
import mediapy as media
import matplotlib.pyplot as plt
import imageio.v3 as iio
```

Importing the necessary libraries

```
<mujoco>
    <compiler angle="degree"/>
    <option><flag contact="enable"/></option>

    <worldbody>
        <camera name="world" pos="0 -22 10" euler="60 0 0"/>

        <!-- Ground -->
        <geom mass="0.1" name="ramp" type="plane" pos="0 0 0" size="50 10 0.1" euler="0 0 0" rgba="0.7 0.7 .9 1" />

        <!-- Ostrich -->
        <body name="ostrich" pos="0 0 {wheel_radius}">

            <camera name="body_cam" mode="track" pos="0 -22 10" euler="60 0 0"/>
            <joint name="ostrich" type="free"/>
```

Defining the environment, including a second camera to account for if the robot falls out of sight of the original “world camera”. Contact is enabled for all of the Geoms until defined otherwise.

```
<!-- Rigid Body -->

<body name="rigid_legs">
    <geom mass="0.1"  name="rolling_leg_1" type="box" size=".1 .1 {still_leg_z}" pos="{still_leg_x} -{still_leg_y} {still_leg_z}" rgba=".5 .2 .9 1" contype="0"/>
    <geom mass="0.5" name="wheel_1" type="sphere" size="{wheel_radius}" pos="{still_leg_x} -{still_leg_y} 0" friction="0" rgba=".2 .2 .5 1"/>

    <geom mass="0.1" name="rolling_leg_2" type="box" size=".1 .1 {still_leg_z}" pos="{still_leg_x} {still_leg_y} {still_leg_z}" rgba=".5 .2 .9 1" contype="0"/>
    <geom mass="0.5" name="wheel_2" type="sphere" size="{wheel_radius}" pos="{still_leg_x} {still_leg_y} 0" friction="0" rgba=".2 .2 .5 1"/>

</body>

<body name="body" pos="0 0 {body_height}">
    <geom mass="0.02" name="body" type="box" size="{body_length} {body_width} .125" pos="0 0 0" euler="0 0 0" rgba="0 1 0 1" contype="0"/>
    <geom mass=".002" name="wheel_3" type="sphere" size="{wheel_radius}" pos="{body_length} 0 0" friction="0" rgba=".2 .2 .5 1"/>
```

Creating the rigid body. This is defined as the main body, the rear legs of the body, and the bearings attached to the rear legs and front face. Note that friction is 0 for each wheel on the assumption that a bearing is “frictionless” relative to the ground.

```
<!-- Leg 1 -->

<body name="l1" pos="{leg_x} -{leg_y} {leg_z}" axisangle="0 1 0 180">

    <!-- Fixed Link -->
    <geom mass="0.001" type="box" size="{fixed} {bar_width} .0005" pos="0 0 0" contype="1" rgba=".1 .1 .1 1"/>


    <!-- Four Bar 1, "Knee" -->
    <body name="l1_b1_1" pos="{b1_1_b} 0 0" axisangle="0 1 0 95">
        <joint name="j1_b1_1" type="hinge" axis="0 1 0" pos="0 0 0" damping="0" range="-140 90" stiffness="0"/>
        <geom mass="0.001" type="box" size="{b1_1} {bar_width} .0005" pos="{b1_1_pos} 0 0" rgba="1 0 0 1"/>

        <body name="l1_b1_2" pos="{b1_2_b} 0 0" axisangle="0 1 0 95">
            <joint name="j1_b1_2" type="hinge" axis="0 1 0" pos="0 0 0" damping="0" range="-140 90" stiffness="0"/>
            <geom mass="0.001" type="box" size="{b1_2} {bar_width} .0005" pos="{b1_2_pos} 0 0" rgba="1 .5 .7 1"/>

            <body name="l1_b1_3" pos="{b1_3_b} 0 0" axisangle="0 1 0 95">
                <joint name="j1_b1_3" type="hinge" axis="0 1 0" pos="0 0 0" damping="0" range="-140 90" stiffness="0"/>
                <geom mass="0.001" type="box" size="{b1_3} {bar_width} .0005" pos="{b1_3_pos} 0 0" rgba="1 0 1 1"/>

                <body name="l1_b1_4" pos="{b1_4_b} 0 0" axisangle="0 1 0 95">
                    <joint name="j1_b1_4" type="hinge" axis="0 1 0" pos="0 0 0" damping="0" range="-140 90" stiffness="0"/>
                    <geom mass="0.001" type="box" size="{b1_4} {bar_width} .0005" pos="{b1_4_pos} 0 0" rgba="0 1 0 1"/>
```

This section defines the four-bar correlating to the knee joint movement on the robot. The rest of the leg from here on out is defined within body “l1” representing Leg 1. All of the joints have limiting ranges to prevent the collapse of four-bar. While the knee four-bar technically begins with the fixed link, the fifth added link is placed with the purpose of welding with the first.

```
<!-- Four Bar 2, "Ankle" -->
<body name="l1_b2_1" pos="{b2_1_b} 0 0" axisangle="0 1 0 0">
    <joint name="j1_b2_1" type="hinge" axis="0 1 0" pos="0 0 0" damping="0.3" range="45 -45" stiffness="0.4"/>
    <geom mass="0.001" type="box" size="{b2_1} {bar_width} .0005" pos="{b2_1_pos} 0 0" rgba="0.5 0.5 0.5 1"/>

    <body name="l1_b2_2" pos="{b2_2_b} 0 0" axisangle="0 1 0 95">
        <joint name="j1_b2_2" type="hinge" axis="0 1 0" pos="0 0 0" damping="0.3" range="45 -45" stiffness="0.4"/>
        <geom mass="0.001" type="box" size="{b2_2} {bar_width} .0005" pos="{b2_2_pos} 0 0" rgba="0 0.5 0.5 1"/>

        <body name="l1_b2_3" pos="{b2_3_b} 0 0" axisangle="0 1 0 95">
            <joint name="j1_b2_3" type="hinge" axis="0 1 0" pos="0 0 0" damping="0.3" range="45 -45" stiffness="0.4"/>
            <geom mass="{foot_mass}" type="box" size="{b2_3} {bar_width} .0005" pos="{b2_3_pos} 0 0" friction=".41" rgba="0.5 0 0.5 1"/>

            <body name="l1_b2_4" pos="{b2_4_b} 0 0" axisangle="0 1 0 95">
                <joint name="j1_b2_4" type="hinge" axis="0 1 0" pos="0 0 0" damping="0.3" range="45 -45" stiffness="0.4"/>
                <geom mass="0.001" type="box" size="{b2_4} {bar_width} .0005" pos="{b2_4_pos} 0 0" rgba="0 0.5 0.5 1"/>
```

Defining the second four-bar corresponding to the ankle joint movement. A specific stiffness and damping is added here to better match the physical model. A friction coefficient is also added to the “foot”.

```
<!-- Transfer -->
<body name="l1_t_1" pos="{t_1_b} 0 0" axisangle="0 1 0 0">
    <joint name="j1_t_1" type="hinge" axis="0 1 0" pos="0 0 0" damping="0" stiffness="0"/>
    <geom mass="0.001" type="box" size="{t_1} {bar_width} .0005" pos="{t_1_pos} 0 0" rgba="0 0.5 0 1"/>

    <body name="l1_t_2" pos="{t_2_b} 0 0" axisangle="0 1 0 60">
        <joint name="j1_t_2" type="hinge" axis="0 1 0" pos="0 0 0" damping="0" range="-45 180" stiffness="0"/>
        <geom mass="0.001" type="box" size="{t_2} {bar_width} .0005" pos="{t_2_pos} 0 0" rgba="0.5 0 0 1"/>

        <body name="l1_t_3" pos="{t_3_b} 0 0" axisangle="0 1 0 100">
            <joint name="j1_t_3" type="hinge" axis="0 1 0" pos="0 0 0" damping="0" stiffness="0"/>
            <geom mass="0.001" type="box" size="{t_3} {bar_width} .0005" pos="{t_3_pos} 0 0" rgba="1 1 0 1"/>
```

The transfer section refers to the triangle structure at the top of the ankle four-bar designed to redirect the pull/pushing motion to a point off of the leg itself.

```
<!-- Knee Motors -->
<body name="l1_knee_Servo" pos="{knee_servo_x} -{knee_servo_y} {knee_servo_z}">
    <geom mass="0.01" type="box" size="{servo_length} {servo_width} {servo_height}" pos="0 0 0" rgba="0 0 1 1"/>

    <body name="l1_knee_horn" pos="{servo_length} -{servo_horn_pos} 0" axisangle="0 1 0 0">
        <joint name="j1_ks_horn" type="hinge" axis="0 1 0" pos="0 0 0" damping="0" stiffness="0" range="-90 90"/>
        <geom mass="0.001" type="box" size="{horn_length} {horn_width} {horn_height}" pos="{servo_horn_x} 0 0" rgba="1 1 1 1"/>

        <body name="l1_ks_1" pos="{ks_1_b} 0 0" axisangle="0 1 0 -5">
            <joint name="j1_ks_1" type="ball" damping="0.6"/>
            <geom mass="0.001" type="box" size="{ks_1} .01 .01" pos="{ks_1_pos} 0 0" contype="1" rgba="1 1 0 1"/>

            <body name="l1_ks_2" pos="{ks_2_b} 0 0" axisangle="0 1 0 -5">
                <joint name="j1_ks_2" type="ball" damping="0.6"/>
                <geom mass="0.001" type="box" size="{ks_2} .01 .01" pos="{ks_2_pos} 0 0" contype="1" rgba="1 1 0 1"/>

                <body name="l1_ks_3" pos="{ks_3_b} 0 0" axisangle="0 1 0 -5">
                    <joint name="j1_ks_3" type="ball" damping="0.6"/>
                    <geom mass="0.001" type="box" size="{ks_3} .01 .01" pos="{ks_3_pos} 0 0" contype="1" rgba="1 1 0 1"/>

                    <body name="l1_ks_4" pos="{ks_4_b} 0 0" axisangle="0 1 0 -5">
                        <joint name="j1_ks_4" type="ball" damping="0.6"/>
                        <geom mass="0.001" type="box" size="{ks_4} .01 .01" pos="{ks_4_pos} 0 0" contype="1" rgba="1 1 0 1"/>

                        <body name="l1_ks_5" pos="{ks_5_b} 0 0" axisangle="0 1 0 -5">
                            <joint name="j1_ks_5" type="ball" damping="0.6"/>
                            <geom mass="0.001" type="box" size="{ks_5} .01 .01" pos="{ks_5_pos} 0 0" contype="1" rgba="1 1 0 1"/>

                            <body name="l1_ks_6" pos="{ks_6_b} 0 0" axisangle="0 1 0 -5">
                                <joint name="j1_ks_6" type="ball" damping="0.6"/>
                                <geom mass="0.1" type="box" size="{ks_6} {bar_width} .0005" pos="{ks_6_pos} 0 0" rgba="0.5 0 0 1"/>
```

This is where the servo connected to the string pulling the ankle four-bar is defined. The servo is defined with its own body and has explicit joint limitations to replicate the actual limitation of the physical servo. The string here is simulated using 5 near massless links connected to each other each with a ball joint defined. The overall string structure has damping to represent the natural stiffness of the fishing wire used.

```
<body name="l1_ankle_Servo" pos="{ankle_servo_x} -{ankle_servo_y} {ankle_servo_z}">
    <geom mass="0.01" type="box" size="{servo_length} {servo_width} {servo_height}" pos="0 0 0" rgba="0 0 1 1"/>

    <body name="l1_ankle_horn" pos="{servo_length} -{servo_horn_pos} 0" axisangle="0 1 0 -90">
        <joint name="j1_as_horn" type="hinge" axis="0 1 0" pos="0 0 0" damping="0" stiffness="0"/>
        <geom mass="0.001" type="box" size="{horn_length} {horn_width} {horn_height}" pos="{servo_horn_x} 0 0" rgba="1 1 1 1"/>

        <body name="l1_as_rod" pos="{as_rod_b} 0 0" axisangle="0 1 0 90">
            <joint name="j1_as_rod" type="hinge" axis="0 1 0" damping="0" stiffness="0.3"/>
            <geom mass="0.0001" type="box" size="{as_rod} .1 .1" pos="{as_rod_pos} -1 0" contype="1" rgba="1 1 0 1"/>

            <body name="l1_as_1" pos="{as_1_b} 0 0" axisangle="0 1 0 90">
                <joint name="j1_as_1" type="ball" damping="0"/>
                <geom mass="0.001" type="box" size="{as_1} {bar_width} .0005" pos="{as_1_pos} -{bar_width} 0" contype="0" rgba="1 0 0 0"/>
```

The servo here corresponds to the servo which controls the knee four-bar. The servo horn here is connected to a link using a hinge joint which itself is connected to a link of the same dimensions as that structure is to be welded to using a ball joint.

```
<equality>
    <weld name="l1_4bar_1" active="true" body1="l1" body2="l1_b1_4" relpose="-{weld_b1_pos} 0 0 1 0 0 0"/>
    <weld name="l1_4bar_2" active="true" body1="l1_b1_3" body2="l1_b2_4" relpose="{weld_b2_pos} 0 0 0 0 1 0"/>
    <weld name="l1_t" active="true" body1="l1_b2_1" body2="l1_t_3" relpose="{weld_t_pos} 0 0 0 0 1 0"/>

    <weld name="l1_ks" active="true" body1="l1_ks_6" body2="l1_t_2" relpose="0 0 0 1 0 0 0"/>
    <weld name="l1_as" active="true" body1="l1_b1_1" body2="l1_as_1" relpose=".7 0 .1 0 0 1 0"/>
```

The weldings for all of the sections.

```
def format_xml (xml, mass):

    d = .05
    #Lengths in inches

    # Still Leg
    still_leg_x = -4
    still_leg_y = 1.5
    still_leg_z = .8
    wheel_radius = .6

    # Body
    body_length = 5
    body_width = 4
    body_height = 2*still_leg_z

    # Moving Leg
    bar_width = 2.5
    leg_x = body_length - 1.1
    leg_y = body_width + bar_width
    leg_z = 0
```

```
fixed = 1

# Four bar 1 Calc
b1_1_pos = .5
b1_1 = b1_1_pos - d
b1_1_b = fixed

b1_2_pos = 1
b1_2 = b1_2_pos - d
b1_2_b = 2*b1_1_pos

b1_3_pos = .75
b1_3 = b1_3_pos - d
b1_3_b = 2*b1_2_pos

b1_4_pos = fixed
b1_4 = b1_4_pos - d
b1_4_b = 2*b1_3_pos
```

This is an example of the calculations done for each of the links to allow for complete adjustment of the link lengths without compromising the structure of the leg. It also universally defines the relative position of the legs and servos of the robot.

```python
def my_multi_controller(model, data):
    t = data.time

    if t > 2:
        pos1 = A*math.cos(2*math.pi*f*t + p1_off) - 1.52
        pos2 = A*math.cos(2*math.pi*f*t + p2_off)
        pos3 = A*math.cos(2*math.pi*f*t + p3_off) - 1.52
        pos4 = A*math.cos(2*math.pi*f*t + p4_off)

        data.ctrl[:] = [pos1, pos2, pos3, pos4]

    return
```

This is the controller designed for each of the motors. Motor 1 and motor 3 each have an offset to account for the different position of the horn when attached to the physical body while maintaining the prescribed range of motion an sg90 servo has.

```python
f_range = 2 #per second
f_step = .4

servo_range = math.pi # approximate pi range
servo_step = math.pi/5

m_range = .004
m_step = .001

parameter_list = []

for m in np.arange(0, m_range, m_step):
    for f in np.arange(0.4, f_range, f_step):
        for p2 in np.arange(0, servo_range, servo_step):
            for p3 in np.arange(0, servo_range, servo_step):
                for p4 in np.arange(0, servo_range, servo_step):
                    parameter_list.append([m, f, 0, p2, p3, p4])
```

This is what was used to generate all of the possible combinations of the given parameters into the form of a list.

```
xs = []

for n, params in enumerate(parameter_list):

    print(params)

    ostrich_xml = format_xml(ostrich_xml, params[0])
    t,x,frames = runXML(ostrich_xml, params[1:], render=False)
    max_x = x.max()
    min_x = x.min()
    xs.append([n, max_x, min_x])
```

This is what was used to run though all the possible parameter combinations. It stores the index of the parameter set used and generates the associated min and max x positional values.

Design Variables

Following the background research, our team wanted to use two four-bar mechanisms to create similar legs to that of an ostrich. As our idea evolved we ended up adding a knee to lift up the leg and it was then pushed by the small four-bar. For the design variable our team focused on: weight, frequency, and the phase difference. For weight, our team wanted to see how adding more or less weight to the legs would change the gait and the speed of the robot. Next for the frequency, our team want to see how creating a high or low frequency would affect the over movement of the robot. Lastly, our team wants to see how the phase difference would change during the changes being made.

Global Parameters

Discuss how you used global parameter sweep(s) and optimization to understand performance as a function of your selected design variable, and why you took that approach.

Overall Results

The data extracted from the model and from the tracker shows that while both the models have a semi-periodic behavior, the Mujoco model has a more chaotic result whereas the actual phototype has a cleaner signal which more obviously correlated with the input cosine function

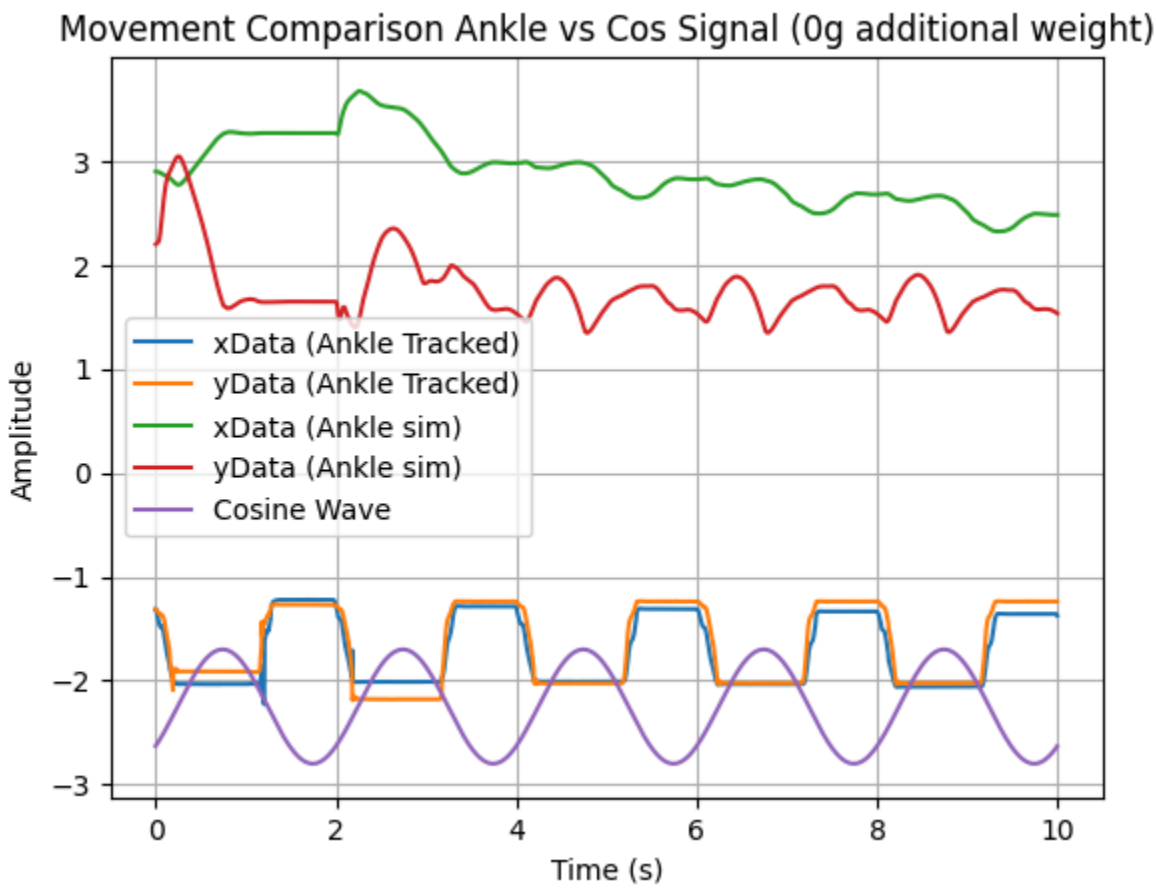


Fig. 23 : Graphed movement comparison

The figures below compare the foot pattern of the simulation with the tracked prototype. Similar to the overall movement comparison, the foot pattern is extremely regular for the track prototype while the simulation has chaotic characteristics. It is noted however, that the simulation also exhibits an ability to move forward in the foot pattern profile.

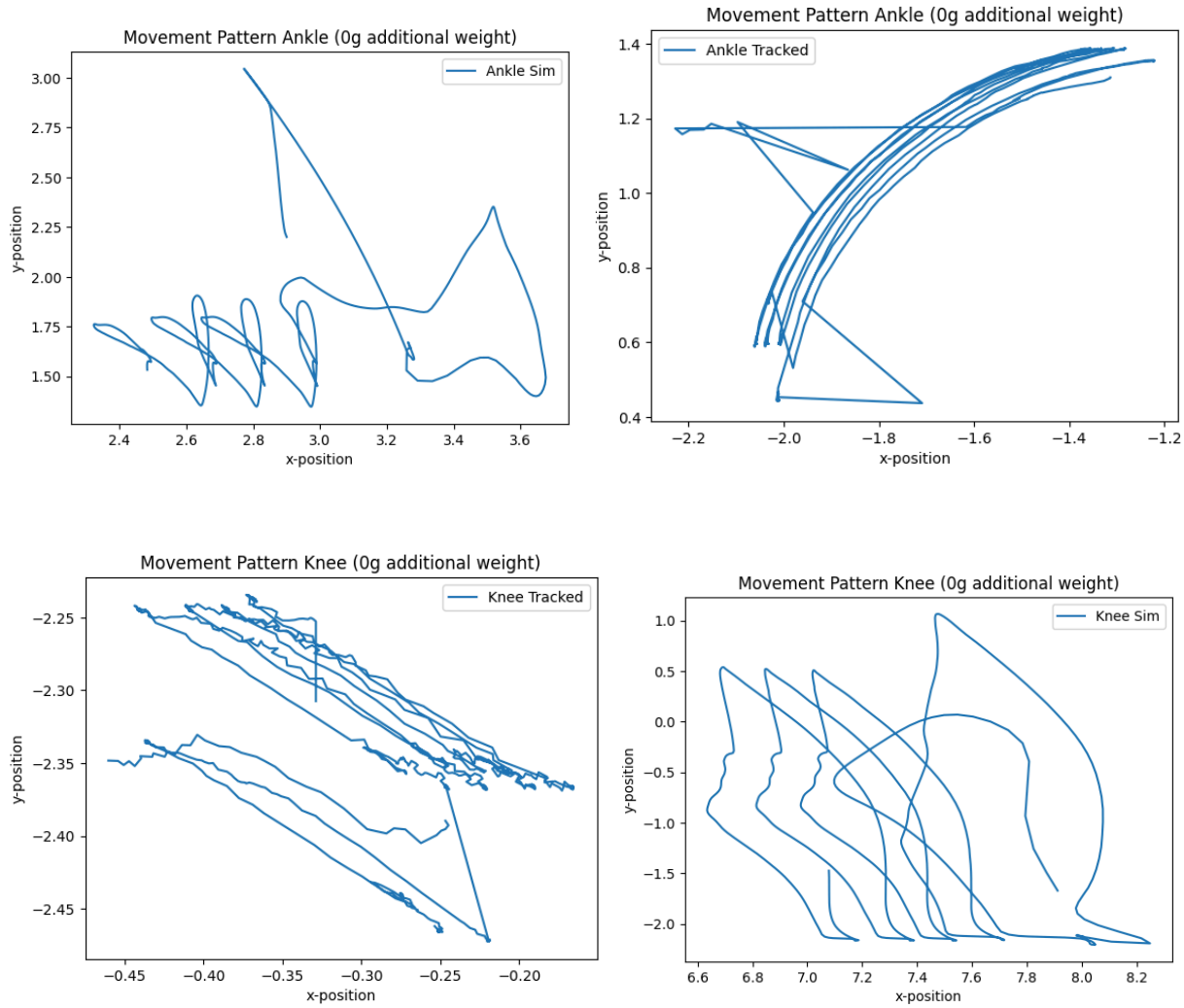


Fig. 24 :

Velocity of the manufactured configuration 0g is 0.603765 inches/min

Velocity of the simulated configuration 0g is 0.8115001824000001 inches/min

Leading Source of Errors

A lot of the errors between the model and prototype accumulate from the fact that the prototype servos tended to have a jerking motion that wasn't present in the model. Additionally, it is possible that the presence of air drag or lack-thereof could have contributed to the models tendency to fall slower than the actual design despite the fact that it had a calculated mass for each of the links to match the prototype.

In order to better match the simulation to the prototype, the first step would likely be to individually characterize the motion of each of the servos. The next would be to manufacture the prototype so that many of the looser fasteners for prototyping could be replaced with something more sturdy. This would all for a greater ability to reproduce the results of experiments and would match closer to the simulation.

What Version 2 would look like

In version 2 of our device there are a few things that we would change to the overall model. The first task would be to fix the DXF file in libreCAD and get rid of the last two joints/links. It was discovered that there were two extra joints. Another change to the libreCAD would be to fix the sizes of the hole that would hold together the smaller four-bar. Another fix in libreCAD would be extend the joints so that it goes all the way through. Lastly in libreCAD we would scale our file to be bigger for easy of building.

For version 2 to be better than the current version, we would need better motors. The current motor do not generate enough power to get our legs to move quickly. If the current motors get caught on anything then they spin until they damage themselves.

To make version 2 look more professional, the body of the robot could be 3D printed. This would help with exact measurements for the motors and motor direction when building the robot. Another way would be to clean up the wiring. The team could do this by using smaller wires, or even step away from the breadboard and create a PCB board to use.

Video of our project

Powerpoint: https://youtu.be/-qGMtcccdSw

Working Robot: https://www.youtube.com/watch?v=LtUuPIIfRWo

Github

https://github.com/deepit-arora/foldable_robotics_ostrich

References

1. D. Aukes, *Foldable Robotics*. 2024.