Respect the Pouch
A Kangaroo Design Report

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*Page numbers have been changed from the original report for the Hoefer publication.
1 Executive Summary

For the ME112: Mechanical Systems Design final project, each team of four was challenged to create a mechanical, battery powered kangaroo crawler. The project was inspired by recent research\(^1\) illustrating that kangaroos rely on their tails as a fifth leg when walking, using it as the primary source of propulsive force. Our mechanical kangaroo was supposed to walk at 10 centimeters per second over a 10.35 meter cobbled pavement section in the new Meyer-Green area. More importantly, the mechanical kangaroo was supposed to emulate the gait of an actual kangaroo.

We prioritized crawler stability, motor output power, and bio-inspired limb movement in our design. Our initial iteration relied on belts and pulleys to transfer power from the motor box to the crawler’s linkages, but after struggling with belt tensioning and alignment, our group moved to a gear-driven transmission for the final design, as seen in Figure 1. Additionally, adjustable feet and removable body panels were incorporated into our design, allowing us to easily calibrate the crawler to walk straight.

The final design used a Tamiya 6-Speed motor box with a 197:1 reduction ratio running at 4.5 Volts from three AA Alkaline batteries. We implemented a custom-built geared drive train to efficiently transmit power from our motor to our linkages. The crawler operated at a 68 RPM linkage cycle with a motor efficiency of approximately 70%. During operation, our kangaroo ran at an average voltage of 3.78 V, drawing 0.732 A. The kangaroo crawler’s tail and front limbs used two separate four-bar linkages that moved in a rocker motion. The kangaroo’s hind legs used another four-bar linkage with a semi-circular coupler point path to lift the tail and front limbs off the ground as they returned forward. During presentation, our kangaroo moved at 14.38 cm/sec over a 10.35 meter section, successfully walking straight across the cobbled pavement\(^2\). The kangaroo crawler’s gait and walking force profile resembled those of a real kangaroo, with the tail and hind legs applying significant propulsive force.

Overall, our group was pleased with the crawler’s performance. However, if allowed further iteration, our group would increase the rocker velocity of the tail and the front limbs, to increase the propulsive force of the tail. This alteration would allow the tail to exert more forward force than the hind legs, more closely matching the force profile of a real kangaroo.

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2 Background

2.1 Overview

The goal of this project was to design a bio-inspired crawler that exhibited the unique pentapedal walking motion of kangaroos. When foraging at slow speeds, kangaroos use their tails as an extra leg to propel themselves forward. This distinctive gait creates an interesting design challenge for mimicking such a motion with a mechanical system. Specifically, our task was to use motor-driven linkages to create a crawler that emulated the anatomic gait of a kangaroo.

For reference, we looked at the results of S. O’Connor et al.\(^3\) “The kangaroo’s tail propels and powers pentapedal locomotion,” to guide our design and break down the motion of a walking kangaroo. The videos and diagrams from this article were crucial in understanding the role of each limb as the kangaroo progressed through its gait. Using this information, we designed and prototyped a battery-powered crawler within various design constraints for speed, size, stability, and anatomical accuracy as described in Section 2.2.

2.2 Kangaroo Demo Logistics

During presentation, our kangaroo crawler had to walk across the raised circular Meyer Green patio (shown in Figure 2). The following requirements had to be met by our crawler:

- be battery-powered;
- have a velocity of $\frac{3}{4}$ body-lengths per second, or approximately 10 cm/sec;
- autonomously maintain a stable, straight trajectory over the cobblestone pavement, depicted in orange in Figure 2;
- exhibit physiologically accurate kangaroo pentapedal locomotion; and
- measure less than 35cm in height and length.

Kangaroos were lined up along one half of the outer circle of the pavement in heats of six. A staggered start was used to reduce the likelihood of collisions at the center. After release, the kangaroos had to walk directly across the pavement in a straight path until they reached the other side of the cobbled pavement. Due to rainy weather, each team was allowed to have one member walk alongside their kangaroo and shield it from the rain with an umbrella. Additionally, each team was granted one act of "divine intervention" to reset the kangaroo in case the kangaroo stalled or deviated from its trajectory.

Given these requirements, our team designed a kangaroo crawler around three separate four-bar linkages to give each set of limbs–hind legs, front legs, and tail–its own distinct motion that combined to give a realistic, pentapedal kangaroo gait. These four bar linkages gave us the flexibility to create the exact motion paths we wanted for each limb and the ability to set the phase of each limb relative to each other.

![Diagram](image)

Figure 2: This diagram shows the layout of Meyer Green and example trajectories of the kangaroo crawlers on final demonstration day.
3 Design Description

3.1 Motor Gearbox Design Goals

Our team’s first purchase was the Tamiya 72005 6-Speed Gearbox. The gearbox has the ability to run at gear ratios of 11.6:1, 29.8:1, 76.5:1, 196.7:1, 505.9:1, and 1300.9:1. We wanted to understand how increasing the gear ratio would affect linkage revolutions. Our goal was to have 1-2 linkage cycles per second in order to move at the required 10 cm/sec. While trying to maximize the output torque of our gearbox to reduce torque load on our motor, we characterized the RPM of the Tamiya gearbox at a 196.7:1 gear ratio over a series of voltage values between 1.5-4.5 Volts. We were able to fit a linear trendline to relate output RPM to input voltage as detailed in the equation below:

\[ \text{Output RPM} = 21.9 * \text{Input Voltage} - 1.4 \]

We know that the operating voltage of 3 AA batteries will fall within a 3 to 4.5 V range. Running at nominal 4.5 Volts, we characterized our output RPM as 97.15 RPM. This equates to approximately 1.6 linkage cycles per second. Running at nominal 3.0 Volts, we characterized the output RPM as 64.3 RPM, or approximately 1.1 linkage cycles per second. These cycle rates fell within our desired range, while also maximizing our output torque, further verifying our gear ratio and voltage choice. More discussion about actual operating voltage and motor performance can be found in Section 4.1.

3.2 Kinematic Motion Design Goals

The pentapedal locomotion of kangaroos was analyzed in order to design linkages that accurately replicated the kangaroo’s gait. Freeze frame video analysis was used to analyze and understand a kangaroo’s gait pattern. Figure 3 shows the kangaroo’s gait in chronological order. We determined that we wanted to replicate the following pattern with our kangaroo crawler:

a) The kangaroo reaches forward with its front limbs.

b) Using its front limb and tail as support, the kangaroo lifts its back legs from the ground.

c) As the tail extends, the back limbs are planted at the front of the kangaroo’s body.

d) Using both its tail and hind limbs, the kangaroo lifts its front limbs and propels forward.

e) Once the tail is fully extended and the back limbs are driven back, the front limbs come down. The tail is brought forward and tucked under the kangaroo’s body.
In addition to studying the kinematic motion, we used S. O’Connor et al. to understand the forces generated by the individual limbs. Figure 4, from the paper, is a condensed graphic breaking down the individual force generation of the limbs throughout the gait. From the paper, we made the following three conclusions:

1. The forelimbs primarily provide vertical support during gait phases (a) through (c). This claim is supported by the negative fore-aft force that the limbs generate through those phases.

2. While the back limbs provide some forward propulsion during phases (d) and (e), they also primarily serve as vertical supports.

3. The majority of the kangaroo’s propulsive force is generated by the tail. As the tail extends in phases (b) through (d), it propels the kangaroo’s body forward.

The implementation of this analysis in our linkage design is discussed in Section 3.3.
3.3 Linkage Design Goals

The linkage design segregated the kangaroo’s limb movement into three four-bar linkages for the front limbs, back limbs, and ont limbs and tail were modeled as having a simple back and forth rocker motion while the back limbs were modeled as having a semi-circular coupler point motion. The primary role of the front limb rocker was to support the front of the kangaroo crawler while the tail rocker served to propel the kangaroo forward. The back limb coupler motion fully supported the crawler’s weight as the rockers of the front limbs and tail returned forward. The three motion groups are plotted in Figure 5.

![Figure 5: Motion profiles for the three linkages: tail motion is shown in yellow, hind leg motion in blue, and front leg motion in red.](image)

From the analysis explained in Section 3.2, we observed that the front limbs only rotate at the “shoulder” joint. The rocker motion of the front limbs prevents the kangaroo crawler from tipping over when it reaches forward and supports the kangaroo’s torso as it shifts its weight onto its back limbs.

The propulsive tuck and extension movement of the kangaroo’s tail was modeled as a rocker. As the rocker moves backward, the tail contacts the ground and propels the kangaroo forward. When phased with the motion of the back limbs, the tail is then lifted from the ground and swept forward to restart the cycle.

The use of rockers for the front limbs and tail required a semi-circular coupler point motion for the back limbs. The back limbs were used to lift the front limbs and tail off the ground as they swept forward. If this were not done, the crawler would simply rock back and forth while staying in place. Conversely, the coupler point’s return path allowed for the back limbs to clear the ground as they cycled forward. Figure 6 shows the movement of the crawler linkages through an entire step cycle.
In addition to designing linkage paths that resembled those of a kangaroo’s limbs, it was important that the velocity profiles of the linkages were smooth. Figure 7 shows that the velocity of the front limbs and tail rockers gradually increases and decreases through the forward and backward sweep. Additionally, both rockers have similar velocities, which is desirable since they move in phase together. A mismatch in velocity would cause one limb to move relative to the other and create an unstable walking motion and, potentially, failure. The back limbs have a similar velocity profile on the ground path with a larger magnitude. However, the hind legs accelerate to a faster velocity on the return path, as shown by the spike in the coupler curve. The slower and smoother velocity profile on the ground path ensures that the movement of the kangaroo crawler is fluid and more force is exerted to move the kangaroo forward.

Figure 6: Gait of our kangaroo as modeled in CAD: red lines represent the kangaroo’s point of contact with the ground.

![Kangaroo Gait Diagram](image)

Figure 7: Tail, hind leg and front leg velocity profiles.

![Velocity Profiles Graph](image)
3.4 Kangaroo Mechanical Design

3.4.1 Design Overview

Figure 8: Render of our final kangaroo design.

The final design and iteration of our kangaroo crawler can be seen in Figure 8 above and Figures 9, 10 and 11 below. The body is made of \( \frac{1}{8} \)" acrylic panels and the gears of \( \frac{1}{4} \)" acrylic. It weighs 900 grams and has dimensions of 33 cm long, 21.5 cm wide and 23 cm high when the tail is fully tucked. All acrylic components were laser cut.

Figure 9: Body plate call out diagram.
As can be seen in Figure 9, the body of our kangaroo crawler consists of four laser cut acrylic plates. The two, hollowed middle plates house our tail linkage and the gears that drive it. They also serve as general support to ensure the rigidity of the assembly. The two outer plates of the crawler house the front and hind leg linkages, serve as rigid supports for the shafts, and give our crawler the appearance of a kangaroo. Note that these four major plates are held together by cross beams that span the distance between the two outer plates.

The design incorporates three linkages as shown in Figure 10. The hind legs are rigidly attached to the coupler link of a four-bar linkage. The tail and front legs are rigidly attached to the rocker of two separate four-bar linkages. Cyanoacrylate (CA) glue was used to fix the crank to the drive shaft for all three linkages.

![Figure 10: Mechanical design call out diagram A.](image)

The various links are connected to each other and to the side plates of the assembly by $\frac{1}{4}$” plastic binding posts of varying length. Foam "springs" were also added to the joint of the hind leg and tail in order to keep their respective feet horizontal to the ground. This protected them from getting caught in uneven pavement and also gave the tail and hind legs a more realistic aesthetic. These features can be seen in Figure 11.

The final design was the third design iteration of our kangaroo crawler. Our first design utilized belts and pulleys to drive our linkages; however, we struggled to reliably fasten the timing pulleys to the shafts and tension the belts between the timing pulleys. This initial design iteration can be seen in Figure 30 in Appendix A.
After consultation with the ME 112 teaching team, we decided that our current design was too wide and that powering our linkages via belt drives not ideal. This led us to our second design iteration shown in Figure 31 in Appendix A. In this design, we decreased the width of the crawler by 25 mm, replaced the belt driven transmission with a gear driven transmission, and modified the cross beams to use mechanical fasteners instead of glue. We found this second design to be adequate for the class, and it showed full walking functionality. However, the duron occasionally delaminated when glued, the design assembly didn’t have perfect alignment, and as a group we didn’t like the aesthetic. This lead us to re-manufacture the design out of acrylic. This final acrylic iteration ended up being our final design. A comparison of our second and final designs can be seen in Figure 32 in Appendix A.

3.4.2 Drivetrain Design

Our drivetrain consists of four drive shafts. The main drive shaft is made of 1/4” aluminum tubing and is rigidly connected to the output shaft of our Tamiya 6-Speed motor box. This coupling was achieved by drilling a 2mm hole in the aluminum tubing, aligning this hole with a hole on the motor output shaft, and pinning the two shafts together. Three secondary 1/4” brass shafts are used to drive the tail, front leg and hind leg linkages, respectively. Attached to each of these shafts is a single acrylic gear that mates directly with a complementary gear on the drive shaft. This allowed us to drive each secondary shaft directly from the main shaft. Note that these complementary gears are identical in pitch and diameter, and CA glue was used to attach each gear to its given shaft. The gear layout in our final design iteration can be seen in Figure 12 on the next page, and the specifications of our three gears can be found in Table 1.
<table>
<thead>
<tr>
<th>Gear Location</th>
<th>Teeth</th>
<th>Diametral Pitch ($^{teeth}_{in}$)</th>
<th>Face Width (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tail Drive Gear</td>
<td>57</td>
<td>22</td>
<td>0.25</td>
</tr>
<tr>
<td>Hind Leg Gear</td>
<td>41</td>
<td>25.4</td>
<td>0.25</td>
</tr>
<tr>
<td>Front Limb Gear</td>
<td>34</td>
<td>22</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Table 1: This table displays the specs for our three custom designed gears.

For our initial design iteration, we used belts instead of gears to drive our secondary shafts from our main shaft. However, this caused two major problems. First the pulleys consistently unglued from the shafts. Second, it was very hard to size belts correctly, especially considering we were using nonadjustable belts. As we changed our design and the locations of our shafts translated, our belts were no longer the correct size. To adjust, we cut and glued the belts to the desired size, a solution that caused unwanted slipping. Additionally, we noticed that our three secondary drive shafts were close to the main drive shaft. As such, we moved to a gear driven transmission, which turned out to be very simple and very reliable. This was the single most important design change we made between our design iterations.

Note that our main shaft and the two secondary shafts driving the front and hind linkages spanned the full width of the crawler with supports on the two side plates. The secondary shaft driving the tail linkage spanned the distance between the two middle plates. CA glue was used to rigidly attach the secondary shafts to the crank of our tail, front leg and hind leg linkage. This required correct phasing of the linkages before gluing, leaving us with linkages that were slightly non-symmetric. However, we designed our legs to be adjustable in order to offset this slight error, a design feature that will be
further discussed in Section 3.4.4. Our linkage orientation can be further seen in Figure 13 and Figure 33 in Appendix A.

Figure 13: Rendering displaying the location of our drivetrain gears.

The Tamiya 6-Speed motor box is supported by a motor platform. This platform connects to one of the side plates through a “tongue and groove” mating system and to the edge of one of the middle plates with CA glue. Furthermore, we found proper shaft alignment to be critical for an efficiently functioning drivetrain. To control alignment, we laser cut all of our components and used bronze sleeve bearings where the main drive shaft mates with the two side body plates. These features can be seen in Figure 14. Note that three AA batteries, mounted to the back of the crawler with CA glue, drive the motor box.

Figure 14: Photograph of the drivetrain showing the Tamiya 6-speed gear box, the main drive shaft and the front limb drive shaft.
3.4.3 Design for Assembly

As touched upon in Section 3.4.1, one of the main problems with our first design iteration was that it was very difficult to assemble and modify. This difficulty resulted from designing without assembly in mind, and left us in a situation where trying to make any change to the kangaroo crawler required partial disassembly. We used hot glue and CA glue to fasten everything. This meant that every time we wanted to take a pulley off of a shaft, or one of the side plates off the kangaroo assembly, we had to remove the glue, make the change, and then re-glue. This often damaged components.

To facilitate ease of assembly, our kangaroo crawler is held together by cross beams that span the distance between the two main side plates of our crawler. We used these supports as an easy way to align the plates of the crawler, ensure symmetry, and guarantee rigidity. Note that both the middle and side body plates have cutout slots to align the cross beams across the crawler. These supports from our final design iteration can be seen in Figure 15.

![Figure 15: Cross beam with tapered pins spanning the two side body plates in our final design iteration.](image)

In order to make assembly easier and increase the flexibility of our design, we decided to implement a tapered pin system into the beam supports for our second and final design iterations. This consisted of adding slotted ends to the cross beams that were extended past the side body plates. A tapered pin was fitted through the slots, pulling the body plates together. This can be seen in Figure 16. This ended up being a fantastic solution and allowed us to quickly remove the main body plates without damaging the crawler. Going even further, the final design iteration implements the same system to hold the two middle plates a fixed distance from the side plates. This ensured that the assembly mimicked the geometry of our CAD model and further allowed us to avoid using glue.
3.4.4 Design for Adjustability

Our assembly had some inherent error that made walking straight unlikely and probably impossible without adjustability. As discussed in Section 3.4.2, manually phasing the linkages lead to slight asymmetry. Also, the laser cutters used to manufacture the acrylic parts had a tolerance of approximately 0.050 inches that led to imperfect mating, particularly between our gears and shafts.

In order to mitigate assembly tolerances, we made the front and hind legs adjustable by separating the limbs into two pieces and rigidly connecting them through a pin and slot mechanism. This gave us control over both the angle and height of the feet relative to the ground. This feature proved to be very important during initial testing at Meyer Green. The crawler had a habit of getting its front limbs caught in the pavement seams, causing it to stall. However, by decreasing the height of our back legs and moving from one to two points of contact in our front legs, we were able to avoid this stalling. These adjustable limbs can be seen in Figure 17.

A final adjustability feature we incorporated were circular spacers. This allowed us to have linkage paths that intersected as we could simply offset their rotation planes, something that was important in trying to imitate a kangaroo’s pentapedal motion. Although these spacers did add friction, this added resistance did not noticeably hinder our motion, and we felt that any energy losses they induced were outweighed by the flexibility and functionality they provided. An example of spacer use on the hind legs can be seen in Figure 18.
Figure 17: View of our kangaroo crawler’s adjustable front and hind legs.

Figure 18: Spacers in our hind leg linkage.
3.5 Free Body Diagrams

Figure 19: This FBD depicts the forces acting on the kangaroo crawler when it is standing on its back limbs.

- \( F_{f,b} \): Back limb friction force
- \( F_{P,b} \): Back limb propulsive force
- \( F_{N1,b} \): Back limb main normal force
- \( \Sigma F_{P,b} \): Foot normal force (distributed)
- \( F_g \): Gravitational force

Dimensions: \( x_1 \) and \( x_2 \) will vary as the back limbs move during gait

\[
\sum F_y = 0 = F_{N1,b} + \sum F_{N2,b} - F_g \\
\Rightarrow F_{N1,b} + \sum F_{N2,b} = F_g
\]

\[
\sum F_x = 0 = F_{P,b} - F_{f,b} \\
\Rightarrow F_{f,b} = F_{P,b}
\]

\[
\sum M_z = 0 = \sum F_{N2,b} x_2 = F_g x_1 \\
\Rightarrow \sum F_{N2,b} = F_g \frac{x_1}{x_2}
\]
Figure 20: This FBD depicts the forces acting on the kangaroo crawler when it is standing on its tail and front limbs.

- $F_{f,t}$: Tail friction force
- $F_{P,t}$: Tail propulsive force
- $F_{N,t}$: Tail normal force
- $F_{f,f}$: Front limb friction force
- $F_{N,f}$: Front limb normal force
- $F_g$: Gravitational force

Dimensions: $x_1$ and $x_2$ will vary as the tail and front limbs move during gait.

\[
\begin{align*}
\Sigma F_y &= 0 = F_{N,t} + F_{N,f} - F_g \\
\Rightarrow F_{N,t} + F_{N,f} &= F_g
\end{align*}
\]

\[
\begin{align*}
\Sigma F_x &= 0 = (F_{P,t} - F_{f,t}) + (F_{P,f} - F_{f,f}) \\
\Rightarrow F_{P,t} + F_{P,f} &= F_{f,t} + F_{f,f}
\end{align*}
\]

\[
\begin{align*}
\Sigma M_z &= 0 = F_{N,f} x_2 + F_g x_1 \\
\Rightarrow \Sigma F_{N,f} &= F_g \frac{x_1}{x_2}
\end{align*}
\]
4 Analysis of Performance

4.1 Motor and Transmission Performance

We characterized the motor’s three essential constants \( (R, k_m, T_{friction}) \) by testing it under no load and stall conditions using a power supply to get true voltage and current values. We also used the following motor mechanical and electrical equations:

\[
V - iR - \omega k_m = 0 \tag{1}
\]

\[
T_{load} = T_{motor} - T_{friction} \tag{2}
\]

At stall, \( \omega = 0 \) and Equation 1 can be reduced to \( R_{motor} = \frac{V}{i_{stall}} \). When no load is applied to the motor, we can determine \( \omega_{no\ load} \) and back out the \( k \) value for our motor. By definition, \( T_{Load} = 0 \) at the no load condition. This reduces Equation 2 to \( T_{motor} = k_m i_{no\ load} - T_{friction} \). Using this logic, we determined the following motor values as well as the electrical and mechanical constants for our motor:

<table>
<thead>
<tr>
<th>Measured Voltage</th>
<th>( i_{stall} )</th>
<th>( i_{no\ load} )</th>
<th>( \omega_{no\ load} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5V</td>
<td>1.93 A</td>
<td>0.12 A</td>
<td>699.5 rad/sec</td>
</tr>
</tbody>
</table>

Table 2: Motor characterization measurements

\[
T_{friction} = 0.00024 \text{ Nm} \tag{3}
\]

\[
k_m = 0.002 \text{ Nm/A} \tag{4}
\]

\[
R_{motor} = 0.77 \Omega \tag{5}
\]

Because our Tamiya motor was rated for 1.5 to 4.5 Volts, we decided to operate in this range in order to avoid unexpected performance. While AA alkaline battery cells are rated nominally at 1.5 Volts, there is internal resistance in the battery. We can back out this internal resistance by measuring the operating voltage (nominally 4.5 V) and current of our kangaroo crawler when walking and using the equation:

\[
\text{Individual AA Battery Resistance} = \frac{\text{Nominal Voltage} - \text{Operating Voltage}}{3 \times \text{Operating Current}}
\]

In our operating current and voltage measurement tests, we saw a two-mode fluctuation in voltage and current values. As Figure 6 in Section 3.3 shows, our kangaroo crawler has two major walking modes that can be correlated to these electrical fluctuations:

- **Mode 1** - states (1) and (2) when the hind legs are in contact with the ground.
- **Mode 2** - states (3), (4), (5), and (6) when the hind legs are off the ground and the tail and front limbs are propelling the kangaroo crawler forward.
Table 3: Operating power of walking modes

We can see in Table 3 that our operating power differs significantly between the two walking modes. This can be mainly attributed to the velocity profile differences in the coupler curves as power is a function of velocity. In order to create a more uniformly delivered power distribution throughout our walking motion, we could decrease the velocity difference between these coupler curves.

We also measured the internal resistance of each battery to be approximately 0.335 Ohms. Understanding our operating input voltage characteristics, we generated a series of plots to characterize our motor performance relative to our operating voltage.

Figure 21: Measured current vs. hypothetical motor efficiency at operating voltage.
As seen in Figure 21, our operating current sits at almost maximum efficiency (70% vs the maximum of 71%). On average during walking, the kangaroo crawler is drawing 0.732 Amps of current. In addition, we can see from Figure 22 that we are well below the maximum operating power of the motor. Knowing that the Amp-Hours of a AA Duracell battery with a 1 Amp discharge rate is 0.83 AH\textsuperscript{4}, we estimate that our kangaroo crawler can run for approximately 50 minutes before running out of battery. This is well above the required run time of approximately 1.2 minutes. This allowed us to comfortably test and present our kangaroo multiple times without running out of power.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{measured_power_vs_omega.png}
\caption{Measured power vs. measured current at operating voltage.}
\end{figure}

4.2 Kinematic Motion Performance

We can also analyze the performance of the kinematic motion and how it relates to the motor’s power output. The equation relating the needed motor electrical power to the crawler’s mechanical power is seen below:

$$\tau \omega (\eta_{system}) = F \cdot v = |F||v|\cos(\theta)$$

The $\theta$ value of the dot product is the angle between the velocity vector, and the force vector $v$ is the velocity of the coupler curve at the point of contact with the ground. $F$ is the reaction force needed to move the crawler forward at a constant rate. More on

how these values were calculated can be found in the Matlab script listed in Appendix C.1. We can calculate $F$ as detailed below:

$$\vec{F} = \sqrt{F_y^2 + F_x^2}$$

$$F_y = m \cdot g \cdot \alpha$$

$$F_x = \mu \cdot F_y$$

$\alpha$ is a scalar constant that takes into account the dynamic movement, oscillations, and impact of the kangaroo crawler. During movement, the center of mass of the crawler changes as the limbs tuck and extend under and beyond the body. Due to this changing center of mass and the impact forces experienced during walking, we assume that $\alpha$ is 1.3 for the movement of the kangaroo crawler. If we compare the resultant theoretical $F_y$ value (11.45 N) with the actual measured normal force profiles illustrated in Figure 27 in Section 4.3, we see that they match well.

$F_y$ and $F_x$ were estimated to be 0 when the linkages were off the ground. $F_y$ is calculated using a conservative two points of contact. This means that we are estimating at least two limbs to be in contact with the ground at any one time, reducing the $y$ force experienced by an individual limb. We found the mass of our kangaroo crawler to be 0.9 kg. We used rubber pads on the bottom of our kangaroo to improve kinetic contact friction with the concrete to avoid slipping; the coefficient of friction ($\mu$) between rubber and concrete is approximately 0.6. Using Matlab, our coupler curves, and our velocity plots, we plotted the required motor power during a full step cycle. This plot can be seen in Figure 23.

![Power Required at Contact Point vs Theta2s at Operating Voltage with 196.7:1 GR](image)

**Figure 23:** Required power model during walking at operating voltage.
As Figure 23 shows, our model indicates that the hind legs require the most power at approximately 1.95 Watts. Our front limbs and tail combined require approximately 1.45 Watts. This power difference illustrates the two modes that we found in our operating voltage and current tests as detailed in Section 4.1 and Table 3. Note that the predicted required power is less than the actual measured required power. This is because in the actual walking that we measured we have some overlap in the two modes when multiple sets of limbs are on the ground at once. In addition, we have power losses in our drivetrain due to shaft misalignment and gear mating. Therefore, the measured power is higher but fits within the sum range of our model.

We can see this difference through an efficiency calculation of the system. We know that, on average, our kangaroo crawler drew \( P_{\text{provided}} = 2.735W \) as detailed in Table 3. We can calculate \( P_{\text{motion}} = \vec{F}_x \times \vec{v}_{\text{measured}} \) to find out the efficiency of our kangaroo crawler moving forward. From our calculations above, we estimated that the force magnitude experienced by the kangaroo crawler in the x-direction (i.e. the direction of movement) is \( \vec{F}_x = 6.89 \) N. Knowing that on average the kangaroo crawler moved at 14.38 cm/sec as discussed further in Section 4.5, we can calculate that:

\[
P_{\text{motion}} = 6.89 \text{ N} \times 0.1438 \text{ m/s} = 0.990 \text{ W}
\]

From these values we can back out the average efficiency of our kangaroo crawler’s motion.

\[
\eta = \frac{P_{\text{motion}}}{P_{\text{provided}}} = \frac{0.99}{2.735} = 36.2\%
\]

Our average efficiency value makes sense given losses from our motor, gearbox, drivetrain gears, and joints. Nevertheless, we designed a system able to provide plenty of power for the linkage path motions without stalling. More discussion on how to improve this efficiency can be found in Section 4.3.

**4.3 Normal and Propulsive Force Performance**

Using a force plate created by TA Isabel Gueble that integrates capacitive touch sensors developed by Alice Wu, we were able to measure the normal and propulsive (shear) forces exerted by our kangaroo during walking. This measuring device allowed us to get a rough estimate of the force profiles of our kangaroo while walking. These force profiles can be seen in Figures 24, 25, and 26 below.

We had our kangaroo walk over the capacitive touch sensor to measure the normal and shear forces exerted by an individual leg as well as the whole tail. We doubled the data value for the front limb and the hind limb as there are two points of contact for each set of limbs during walking.

120
Figure 24: Measured force profile of the kangaroo crawler’s tail.

Figure 25: Measured force profile of the kangaroo crawler’s front leg.
Overall, we were pleased that our kangaroo’s values matched our kinematic motion design goals and the actual anatomic motion of a walking kangaroo. As seen in Figure 27, the normal force of the crawler limbs match well with the project’s inspiration research mentioned in Section 3.2 and provide plenty of normal force to support the weight of the crawler. While the tail does not exert the most propulsive force (the hind legs do), we can see in testing and in the data that the tail does significantly move the kangaroo crawler forward.

How might we improve this force profile to more accurately resemble that of a real kangaroo? Increasing the rocker velocity of the tail would allow the tail to contact the ground with more speed and increase the reaction force (i.e. propulsive force) with the ground based on Newton’s Second Law, $F = ma$. As seen in Figure 7, the tail and front limbs have similar velocity profiles in order to stay in phase and move the kangaroo forward while the hind legs are off the ground. Therefore, both velocities must be increased in order to maintain stable motion. By elongating the crank arm and moving the crank and coupler interface point closer to fixed rocker point, we can increase the lateral velocity of the rocker. This would also elongate the path of the rocker, meaning that we would be applying force over a long distance and increasing the applied work ($W = F \Delta X$).

In addition, we can improve our efficiency by reducing the excess normal force applied by the kangaroo crawler. We apply over 11 N of normal force on each limb as detailed in Figure 27 and only require approximately 9N of normal force based on the weight of our kangaroo crawler (i.e., $m \times g$). Reducing this excess normal force can be achieved by modifying the coupler curve trajectories to be more parallel to the ground. This will generate more force in the x-direction, thereby increasing walking velocity and $P_{motion}$. These changes would help improve the anatomic motion of our kangaroo crawler.
4.4 Drivetrain Gear Strength Estimate

While our group was confident in the strength of the Tamiya 6-Speed Gearbox gears, we performed Lewis stress analysis on our acrylic drivetrain gears to ensure that they would not fail. Lewis stress, which is the bending stress on the gear teeth when treated as cantilevered beams, is expressed as:

$$\sigma_{\text{Lewis}} = \frac{F_{\text{tan}}P_d}{bJ_{\text{Lewis}}}K_mK_oK_v$$

The Lewis stress accounts for gear-specific factors like rigidity of mountings, uniformity of power supply, and how fast the gear is rotating. These variables are represented by constants $K_m$, $K_o$, $K_v$, respectively. We wanted to primarily understand the Lewis stress during stall as this is when the torque on the gears is highest and therefore the forces between the gear teeth are at a maximum. We knew that the ultimate tensile strength of acrylic is approximately 10 ksi. Therefore, we wanted Lewis stresses well below this failure value.

$$\sigma_{\text{Lewis, max}} = 5.336 \text{ ksi}$$
$$\sigma_{\text{yield}} = 10.0 \text{ ksi}$$
$$\sigma_{\text{Lewis}} < \sigma_{\text{yield}}$$

These K factors, as well as the geometry factor $J$, were all chosen from tables and curves found in Juvinall and Marshek’s Fundamentals of Machine Component Design.

Figure 28: Rendering of the drivetrain, visually illustrating the different gear meshes with different colors.

The corresponding gears shown in Figure 28 are detailed in Table 4, which compiles the calculated Lewis stress as well as other values pertaining to the drivetrain. See the Matlab code in Appendix C.2 for reference values. As seen in Figure 29, the maximum Lewis stress occurs on the hind leg drive train gears. This is because we were forced to use a smaller gear module value (1 mm vs 1.125 mm) for better meshing. Comparing this maximum experienced stress ($\sigma_{\text{Lewis}} = 5.336$ ksi) with the ultimate tensile strength of acrylic ($\sigma_{\text{yield}} = 10$ ksi), we see that the most vulnerable gear is operating well below the yield stress, and therefore our gear train should not be subject to any material failure or deformation during its lifespan.

<table>
<thead>
<tr>
<th>Gear Location</th>
<th>Teeth</th>
<th>Diametral Pitch (teeth/m)</th>
<th>Face Width (in)</th>
<th>$F_{\text{tan}}$ (lbf)</th>
<th>$J_{\text{Lewis}}$</th>
<th>$\sigma_{\text{Lewis}}$ (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tail Drive Gear</td>
<td>57</td>
<td>22</td>
<td>0.25</td>
<td>1.99</td>
<td>0.46</td>
<td>2.75</td>
</tr>
<tr>
<td>Tail Gear</td>
<td>57</td>
<td>22</td>
<td>0.25</td>
<td>1.99</td>
<td>0.46</td>
<td>2.75</td>
</tr>
<tr>
<td>Hind Leg Drive Gear</td>
<td>41</td>
<td>25.4</td>
<td>0.25</td>
<td>3.20</td>
<td>0.44</td>
<td>5.336</td>
</tr>
<tr>
<td>Hind Leg Gear</td>
<td>41</td>
<td>25.4</td>
<td>0.25</td>
<td>3.20</td>
<td>0.44</td>
<td>5.336</td>
</tr>
<tr>
<td>Front Limb Drive Gear</td>
<td>34</td>
<td>22</td>
<td>0.25</td>
<td>3.339</td>
<td>0.41</td>
<td>5.18</td>
</tr>
<tr>
<td>Front Limb Gear</td>
<td>34</td>
<td>22</td>
<td>0.25</td>
<td>3.339</td>
<td>0.41</td>
<td>5.18</td>
</tr>
</tbody>
</table>

Table 4: This table lists each gear along with its relevant dimensions, forces, and stresses.
4.5 Gameday Performance

Our kangaroo performed extremely well on game day. With rain falling, our team used heat shrink on all wire connections and wrapped our battery housings in electrical tape to waterproof our kangaroo crawler. The kangaroo crawler walked the 10.36 meters across Meyer Green, going through the middle, in 72 seconds. The crawler’s average velocity was 14.38 cm/sec, above the desired 10cm/sec benchmark. Everything functioned well; our kangaroo’s feet did not get caught in the brick grooves, and we narrowly avoided a collision with another team’s kangaroo that ventured into our path. Overall, our team was extremely happy with seeing our design work well. A video of the final day performance can be found here\textsuperscript{7}.

5 Redesign

Overall, we are very happy with how our final kangaroo crawler turned out. We achieved full functionality in an elegant way, and produced a robust and reliable machine. However, if given three more weeks and $300 to improve our design, there are five things that we would want to implement:

1. Improve our linkage curves to give the most realistic kangaroo pentapedal motion possible. We are happy with our linkages now, and they proved to give a fairly realistic gait, however iteration upon our linkage designs would allow us to refine our motion and make it as lifelike as possible. Specifically, we would want our tail linkage to have more propulsive power, which could be achieved by increasing the speed of its rocker motion as discussed in Section 4.3.

2. Implement keyed shafts and couplers as a way of fixing our gears in place without the use of CA glue. This would allow us to change their position on the shaft at will and streamline assembly. In our current design, we had one chance to glue the gears correctly in place; a difficult, inexact, and frustrating process.

3. Rigidly attach our shafts to our linkage cranks through pinned connections. In our current design, CA glue is used to make this connection, however this is an inexact and unchangeable solution. It also forced us to phase our linkages by eye which added error to our design. With a pin system, a couple holes could be drilled, allowing us to change phase while still retaining a fixed connection.

4. Reduce the scale of our design. This would give us a lighter kangaroo that draws less current and requires less power, which in commercial applications would allow it to run for longer on a given battery supply.

5. Increase the surface area of the feet. The front and hind legs of our kangaroo occasionally got in the cracks of uneven pavement, probably due to their thin and pointed profile. Increasing the width and contact area of the feet could help avoid such stalling and give our kangaroo the ability to function on a wider variety of surfaces.
6 Conclusions

The final iteration of our kangaroo crawler ran smoothly and consistently walked across the cobbled pavement of Meyer Green with a realistic kangaroo pentapedal motion. The crawler moved at a velocity of 14.38 cm/sec, above the desired 10 cm/sec. As such, we believe our ultimate kangaroo design was a resounding success.

The only problem we faced while testing was that the front and hind limbs would occasionally get stuck in the cracks of the cobbled pavement and cause the crawler to stall. With the adjustable limb mechanism, we were able to calibrate the crawler to avoid such stalling. However, increasing the width and contact area of our kangaroo’s feet would also provide more stability and functionality on uneven surfaces.

Moving forward, the only fundamental change to our design that we would recommend would be to optimize our linkage coupler point motion curves. Specifically, in order to more accurately model the pentapedal motion of a kangaroo, we would want to have our tail apply more propulsive force. This could be achieved by increasing the crank speed of our tail linkage. This could also be achieved by lengthening the backward stroke of the tail. With a longer stroke, the back tail would propel the crawler forward over a longer distance.

Past these main improvements, small changes such as using keyed shafts and pinned connections between our shafts and linkage cranks would improve assembly, serviceability, and rigidity. However, we feel that our final kangaroo design is very robust and only requires incremental tweaks rather than major changes in search of increased functionality.
Appendices

A Additional Images

Figure 30: Initial kangaroo crawler design iteration.

Figure 31: Secondary kangaroo crawler design iteration.
Figure 32: Comparison between our second and final kangaroo crawler designs.

Figure 33: Photograph showing our drivetrain gears through the side body plate.
B Table of Variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau$</td>
<td>Motor output torque in Newton·Meters</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Motor angular velocity in radians per second or revolutions per minute</td>
</tr>
<tr>
<td>$\eta_{\text{efficiency}}$</td>
<td>The total efficiency of the drivetrain and motor empirically found</td>
</tr>
<tr>
<td>$F$</td>
<td>The force magnitude applied by the kangaroo to the ground while walking in Newtons</td>
</tr>
<tr>
<td>$v$</td>
<td>The coupler point velocity of the kangaroo limbs in meters per second</td>
</tr>
<tr>
<td>$\theta$</td>
<td>The angle between the force and velocity vector at the point of contact with the ground in radians</td>
</tr>
<tr>
<td>$F_x$</td>
<td>The force in the $x$ direction estimated to be equal to or less than $\mu \cdot m \cdot g$ in Newtons</td>
</tr>
<tr>
<td>$F_y$</td>
<td>The force in the $y$ direction estimated to be the weight of the kangaroo crawler, $m \cdot g$ in Newtons</td>
</tr>
<tr>
<td>$m$</td>
<td>The mass of the crawler in kg</td>
</tr>
<tr>
<td>$g$</td>
<td>The gravitation acceleration, $9.81 \text{ m/s}^2$</td>
</tr>
<tr>
<td>$\mu$</td>
<td>The kinetic coefficient of friction between the walking surface and the kangaroo crawler foot material</td>
</tr>
<tr>
<td>$\sigma_{\text{Lewis}}$</td>
<td>The Lewis stress applied on a gear in ksi</td>
</tr>
<tr>
<td>$F_t$</td>
<td>The tangential force applied to a specific gear tooth in Newtons</td>
</tr>
<tr>
<td>$P_b$</td>
<td>The diametral pitch of a gear in inches</td>
</tr>
<tr>
<td>$b$</td>
<td>The face width of a gear in inches</td>
</tr>
<tr>
<td>$J_{\text{Lewis}}$</td>
<td>The Lewis geometry factor</td>
</tr>
<tr>
<td>$K_m$</td>
<td>The mounting factor</td>
</tr>
<tr>
<td>$K_o$</td>
<td>The overload factor</td>
</tr>
<tr>
<td>$K_v$</td>
<td>The velocity factor</td>
</tr>
<tr>
<td>$\sigma_{\text{Lewis max}}$</td>
<td>The maximum Lewis stress for the kangaroo crawler drivetrain</td>
</tr>
<tr>
<td>$\sigma_{\text{yield}}$</td>
<td>The ultimate tensile strength of acrylic, known to be 10 ksi</td>
</tr>
</tbody>
</table>

Table 5: This table displays all the variables and their associated definitions listed in the report in order.

C Matlab Code

C.1 Kangaroo Crawler Kinematics Matlab

Can be downloaded from: [https://www.dropbox.com/s/652v4me5cw71mgk/KangarooKinematics%20Matlab.zip?dl=0](https://www.dropbox.com/s/652v4me5cw71mgk/KangarooKinematics%20Matlab.zip?dl=0)

C.2 Drivetrain Lewis Stress Matlab

Can be downloaded from: [https://www.dropbox.com/s/652v4me5cw71mgk/KangarooKinematics%20Matlab.zip?dl=0](https://www.dropbox.com/s/652v4me5cw71mgk/KangarooKinematics%20Matlab.zip?dl=0)