Bipedal Robot
Design Report

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ME 112: Mechanical Systems Design

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INSTRUCTOR FOREWORD

The design report by Devon MacNeil, Ben Fearon, Chase Porter and Matthew Stevens accompanies their entry in the ME112 final project, “Bipedal Creatures.” The project was inspired by the observation that among earth’s creatures, only two are inherently bipedal: humans and birds. Of these, birds have the arguably more efficient and stable solution, having benefitted from millions of years of dinosaurian evolution.

This design team’s report describes a particularly effective solution to this year’s challenge. The team realized early on that “It’s all about stability.” They developed a clever linkage system that keeps the feet parallel to the ground and the center of mass centered over the feet for a stable, emu-like gait. They were also able to correlate measurements taken with an instrumented force plate with those from their models, and their solution was voted one of the three “most biomimetic” entries among 36 designs in the class. The team’s report well captures the essence of the work and does a great job describing their unique design and how it performs.

—Mark R. Cutkosky and Paul Mitiguy
Bipedal Robot Design Report

ME 112

Team Emo Emu
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Executive Summary

For the final project in Mechanical Systems Design (ME112) each group was challenged to create a battery-powered bipedal robot, able to walk a distance of 1.5 meters at a minimum speed of 3 cm per second. The robots were to be inspired by either a type of bird or dinosaur, and a design goal was to make the bipedal robot as biomimetic as possible while still being able to perform successfully during the final presentation.

After preliminary research, our team decided to make a robot that emulated an emu. We believed that the emu’s large feet, smooth gate, and even weight distribution over the legs would help make our bird successful. To actuate the feet, we chose an “inverted knee” configuration that mimics the knee joint in a walking bird. Our linkage is an augmented four-bar mechanism with parallelograms that keep the feet level relative to the ground to improve balance.

An initial iteration of Emo Emu experienced difficulty in walking smoothly and consistently. After receiving feedback during a design review, we realized we needed to reduce the amount of backlash and deflection in our linkage system and legs. We added steel tubing between various elements of the linkages and braced all connections. We also added a sprocket and chain system to ensure that all components of the parallelogram mechanism remained in phase. These changes allowed our bird to walk with an even and consistent gait at approximately 12 cm/s. We powered the mechanism using a Tamiya 6 speed gearbox with a 196.7:1 reduction ratio, operating at an efficiency of 62% on 3 volts, supplied by four AA batteries.
Having satisfied the functional requirements for a bipedal walking machine, we turned our attention to aesthetics. An all-white body with reflective acrylic extremities created the emu’s silhouette (if not its coloration). At the close of final presentations our walker was voted one of the most biomimetic robots for this year’s ME112: Mechanical Systems Design.

We are pleased with our emu’s success in terms of performance and design. If we were able to produce another iteration, we would reshape the feet to land on a straighter path, and experiment with materials that provide better traction against the ground.
# Table of Contents

1. Background ........................................................................................................... 5  
   1.1 Overview ........................................................................................................ 5  
   1.2 Bipedal Robot Requirements ........................................................................ 6  

2. Design Description .................................................................................................. 8  
   2.1 Motor Gearbox ................................................................................................ 10  
   2.2 Kinematic Motion Design Goals ..................................................................... 10  
   2.3 Linkage Design Goals ..................................................................................... 12  
   2.4 Coupler Curves ............................................................................................... 13  
   2.5 Foot Leveling Design ...................................................................................... 16  
   2.6 Final Design & FBDs ...................................................................................... 19  

3. Analysis of Performance ........................................................................................ 22  
   3.1 Motor Characterization .................................................................................. 22  
   3.2 Motor Efficiency and Battery Configuration .................................................. 23  
   3.2 Power Transmission Efficiency ...................................................................... 26  
   3.3 Force Plate Testing and Analysis .................................................................... 28  
   3.4 Gameday Performance .................................................................................... 29  

4. Bird Redesign .......................................................................................................... 31  

Bibliography ............................................................................................................... 33  

Appendices .................................................................................................................. 34  
   A. Process Photos .................................................................................................. 34  
   B. Full Prototypes .................................................................................................. 37  
   C. Plots ................................................................................................................... 39  
   D. Matlab Scripts ................................................................................................... 40
1. **Background**

1.1 **Overview**

The goal of this project was to create a bipedal robot inspired by a bird or dinosaur. First, we researched a variety of birds and analyzed their gaits. We used this research to help guide the goal of the project: design a robot with motor-driven linkages that reflected the gait of a bird.

In order to create a bioinspired robot, we referenced Abourachid, Anick, and Vincent Hugel’s "The Natural Bipeds, Birds and Humans: An Inspiration for Bipedal Robots." This research informed us about the key difference of bipedal motion between humans and birds; it enlightened us as to what made bipedal motion in birds special. In short, we needed to design a bipedal robot that did not walk erect, but crouched with the joints flexed, and the trunk hanging horizontally between the thighs.¹ Next, we analyzed several birds walking including an Ostrich, Flamingo, Blue-Footed Booby, and Emu. We chose an emu to guide our bipedal robot because of their low center of mass and their gait that does not include lateral wobbling, but rather stays true to forward motion.

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1.2 Bipedal Robot Requirements

Our final deliverable required that our bird walk across a relatively smooth surface with a stable bipedal gait. The restrictions and requirements were as follows:

- Exhibit a stable and smooth bipedal gait that is not remote-controlled;
- Be battery-powered;
- Resemble a chosen creature that is bipedal physically and kinematically;
- Walk at a pace of at least 3 cm/sec;
- Not exceed 20 cm in height.

During the final challenge, the bipedal robots were lined up three at a time on each side of the Meyer green pavement along the outer edge. The walkers were required to walk across a determined 1.5 m distance track, followed by continuous successful movement in a straight line over the cobblestone surface that covers the inner diameter of the pavement as shown in Fig. 2 below. Additionally, the walker had to exhibit biomimetic locomotion and show clear bioinspired features in its design. However, it was noted that having emulative biomimetic motion was more important than aesthetics in evaluation criteria. These requirements and the characteristics of gameday surface conditions guided us to design a four bar linkage with supporting parallelograms that both maintain foot levelness and smooth bipedal motion. Please see section 2 for design details.
Figure 2: Diagram of gameday layout characteristics at Meyer Green.
2. Design Description

This section outlines the mechanical, biomimetic, and aesthetic design choices that went into the final design of our robotic Emu, pictured below. The key features of the bird are outlined in Fig. 3.
Figure 3: Final design characteristics with main parts highlighted and named.
2.1 Motor Gearbox

Our team utilized a Tamiya 72005 6-Speed Gearbox to drive the motion of our emu. This modular gearbox provides configurations that generate gear ratios of 11.6:1, 29.8:1, 76.5:1, 196.7:1, 505.9:1, and 1300.9:1. Because our design had to move at a speed greater than 3 cm/s, we knew our linkages would have to rotate at a speed of about 1 cycle per second. We built the motor to operate with a gear ratio of 196.7 and began testing over a series of input voltage values ranging from 1.5 V to 4.5V.

In collecting data, we knew the operating voltage of 2 AA batteries connected in series would fall around 3V. Running at a nominal 1.5V, we found our output RPM to be 28 RPM. This translates to roughly 0.47 linkage cycles per second. Running at a nominal 3V, we found our output RPM to be 44 RPM. Running at a nominal 4.5V, we found our output to be 80 RPM, which translates to roughly 1.3 linkage cycles per second. The linear speed generated from the 1.5V proved to be too slow for desirable walking speed. The 3V nominal voltage, with 1 linkage cycle per second generated a linear speed of 12.35 cm/s. Further, the output torque at each stage was maximized, leading us to believe that we had found the right gear ratio for our design. More information regarding our final operating voltage and motor performance can be found below in section 3.1.

2.2 Kinematic Motion Design Goals

We analyzed the bipedal motion of the emu in order to design a system of linkages that would mimic the biological movement of its limbs. By using slowed down footage of side profile views of emu’s
walking, we collected information regarding its unique bipedal gait. Fig. 4 shows this particular gait and its associated movements.

In using this information, we designed Working Model simulations that would generate consistent movement with specific linkage patterns that are modeled after specific limb and joint movements of an actual emu. Fig. 5 below displays our first Working Model that implements our preliminary linkage system and emulates the inverted knee, gait, and elliptical foot path characteristic of the emu.

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2.3 Linkage Design Goals

The linkage design that we implemented was a supported four-bar linkage system for both legs. This design consisted of a rocker, coupler, and crank, each of which was supported by their respective secondary linkages. Because we wanted to emulate the biological design of the emu, we chose to implement an “inverted knee” design for our coupler that is connected on one end by the rocker, another by the secondary coupler, and a third at the feet, creating the coupler point.
Each side of the design operates under identical linkage systems that are set 180 degrees out of phase in order to ensure the proper footstep pattern and reduce lateral movement. We included a sprocket and chain that distributes power from the motor’s output shaft to a secondary shaft, in order to ensure that the secondary crank would always be in phase with the primary crank. This allowed for a less wobbly gait and ensured a complementary linkage motion. The associated motion of the coupler design is analyzed in the following section.

2.4 Coupler Curves

We began by utilizing Saltire Software’s Crank Rocker Atlas, an open source, online interactive platform that utilized Hrones-Nelson’s Atlas. We settled on a curve that looked generally flat and was faster in the air than it was on the ground. We then proportionally scaled the linkage lengths down to fit the total upper height constraint of 20 cm. After modeling a few coupler curves on Working Model and analyzing velocity data, we chose the following coupler curve and four-bar linkage design shown in Fig. 6.
Figure 6: Screenshot of a Working Model simulation of our coupler curve and linkage dimensions, fixed in free space via the green ground link. All distance units are in meters.

The Working Model simulation pictured in Fig. 6 demonstrates our final four-bar linkage system, running at the motor speed of 47 RPM, or 282 deg/sec; we measured the output angular speed of our Tamiya Gearbox using a tachometer to measure the 47 RPM. The coupler point data, exported from the Working Model simulation, pictured in Fig. 7, indicates that the maximum velocity of the foot in the air, with respect to the body of the bird, is theoretically 0.271 m/s and -0.205 m/s on the ground. The average velocity of the foot in the air, with respect to the body of the bird, is 0.1562 m/s and -0.1271 m/s.
Figure 7: Plot of the coupler point’s velocity, or the theoretical velocity of the foot. The red shaded portions visually indicate data for when the foot is in the air, moving “forward”.

on the ground. This Working Model Simulation of our final design calculates that the foot spends $0.13 \pm 0.005$ seconds longer on the ground. This is beneficial in order to guarantee that there will be no instance in the gait where both feet are “in the air” and to minimize the time the robot is only supported by one foot.

This data analysis would suggest that the theoretical forward movement of the bird’s body with respect to the world is around $0.1271 \text{ m/s}$, or $12.71 \text{ cm/s}$, on average. This theoretical number will
later be compared to the actual speed of the bird in order to account for realized losses due to slippage, tolerances, and joint friction.

2.5 Foot Leveling Design

As outlined earlier, the linkage system is considered a supported four-bar linkage as it employs a series of secondary linkages that form two parallelograms. The primary crank is rigidly fixed to the motor’s output shaft and the secondary crank is rigidly fixed to a secondary crank shaft. The primary and secondary cranks both rotate in the same direction at the same angular velocity as the power is translated from the motor’s output shaft to the secondary drive shaft through a sprocket and chain system. These parallelograms, highlighted in Fig. 8 below, geometrically ensure that the foot will maintain a level alignment relative to the ground.

Figure 8: Image of geometries within the linkage system, primarily two parallelograms, ensuring parallelism between the feet and ground.
Figure 9: Still frames from a video of an early prototype exhibiting parallelogram collapse.
Our original prototype did not include the secondary drive shaft, causing the crank parallelogram to ambiguously fall into itself, a problem illustrated in the images in Fig. 9. In these images of our bird walking upside down, the primary crank is highlighted in green and the secondary crank is in dark red. The secondary crank, in this prototype, was not connected to a secondary drive shaft and was instead freely rotating on a screw post attached to the white body. In the image on the right, the secondary crank is not parallel with the primary drive crank and has rotated out of alignment; causing the foot in the foreground to noticeably angle upwards. Ideally, in order to maintain its parallelogram and thus keep the foot parallel to the ground, the secondary crank would have been in the drawn pink box. This problem is simulated below.

Figure 10: Screenshot comparing two Working Model simulations with the same four-bar linkage systems. The image at right highlights our original prototype’s secondary crank’s tendency to turn out of phase with the primary drive crank.
Note that in the left Working Model diagram of Fig. 10 the cranks form a perfect parallelogram. In contrast, the image on the right demonstrates the issue our first prototypes would generate. In the second image, the primary crank is at the same angle as it is in the first image; however, the secondary crank has not rotated in parallel with it due to compounding tolerances and imprecisions in construction, creating an almost-perfect parallelogram. In order to counteract this parallelogram collapse issue, we inserted a shaft that rigidly attached to the secondary cranks. We then connected this shaft to the motor’s output shaft via a chain. This chain translated the power to the secondary drive shaft, ensuring that the cranks would never rotate out of phase.

2.6 Final Design & FBDs

The completed design utilizes laser cut 0.20 inch mirrored acrylic for the linkages and ⅛ inch white acrylic for the body. Steel tubing was used for the secondary crank shaft and the stabilizing rod that the rockers freely rotate on; smaller segments were also used to extend the motor’s output shaft. All cranks are rigidly attached to the crank shafts via lateral metal pins that resist free rotation. The radius of the linkages was increased, relative to earlier designs, to provide more surface area contact at the joints and improve stability. The whole design weighs 554 grams and is 18 cm tall at the peak of its step.

The Tamiya 6-Speed Gearbox is bolted to the base of the white body and two 2x AA battery packs are glued to the bottom of the body. In order to resist slipping, we wrapped rubber bands around the corners of the feet that had a much higher friction...
coefficient than the smooth acrylic. The modularity of this traction system allowed us to correct the bird’s walking direction; we eventually added one extra rubber band to the right foot so the bird would not curve to the right.

Figure 11: Free body diagrams for two different views of the emu in mid-step. The center of mass is indicated by the checkered circle. Force labels are defined in the following table:
### Label | Significance
--- | ---
Fg | Force of gravity, acting on the emu from its center of mass.
Fn | Normal force on the emu’s foot, acting directly below the center of mass
Fm | Force exerted on the foot of the emu by the motor (via the leg linkage)
Ff | Static friction on the emu’s foot, causing it to resist slipping

| y-axis force balance | z-axis force balance |
--- | --- |
\[ \Sigma F_y = F_n + F_g = 0 \]  
\[ \rightarrow F_n = -F_g \] | \[ \Sigma F_z = F_f + \Sigma F_m = 0 \]  
\[ \rightarrow F_f = \mu mg = \Sigma F_m \]
3. Analysis of Performance

3.1 Motor Characterization

Tamiya provides motor characterization information for its six-speed gearbox (which we used to power the emu), but this data proved to be inaccurate in our case. Our guess is that the Tamiya information was based on a 3 Ohm motor resistance, while our particular motor had a significantly lower resistance (we measured 0.65 Ohms). So, in order to obtain the motor constant and the motor resistance, we performed a stall test and a no-load test.

In the stall case, motor angular speed is zero, allowing equation (1) to be rewritten as equation (2).

\[
V - iR_m - k_m w = 0 \quad (1)
\]
\[
V/i_{\text{stall}} = R_m \quad (2)
\]

Plugging the the voltage and stall current \(i_{\text{stall}}\), we can solve for motor resistance. The numerical results from our stall test are shown in the table below.

<table>
<thead>
<tr>
<th>(i_{\text{stall}}) (A)</th>
<th>Voltage (V)</th>
<th>(R_m) (Ohms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.32</td>
<td>1.50</td>
<td>0.65</td>
</tr>
</tbody>
</table>

We performed a no-load test to identify the motor constant \(k_m\). During this test, we ran the motor at constant voltage under no load, and used a tachometer to identify its angular velocity. Plug-
ging the known values for voltage, current \(i_{nl}\), angular velocity \(w_{nl}\), and resistance \(R_m\) into equation (1), we can solve for \(k_m\) (shown in equation 3).

\[
(V - i_{nl}R_m)/w_{nl} = k_m \quad (3)
\]

Numerical values from our test are shown below:

<table>
<thead>
<tr>
<th>(i_{nl}) (A)</th>
<th>(w_{nl}) (rad/sec)</th>
<th>Voltage (V)</th>
<th>(k_m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.17</td>
<td>1340.40</td>
<td>3.0</td>
<td>0.0022</td>
</tr>
</tbody>
</table>

The found values \(k_m\) and \(R_m\) allow us to plot aspects of our motor’s performance (torque, power, and efficiency) across a range of speeds. These plots are shown in the Appendix, and discussed in Section 3.2.

### 3.2 Motor Efficiency and Battery Configuration

Since the Tamiya motor has a recommended operating voltage of 1-4.5V, we chose to begin testing in the center of that range, at 3V. During initial walking tests, we counted crank rotations over a set period of time, and multiplied by our drivetrain ratio to identify operational motor RPM. This allowed us to identify our point of operation on the motor’s characterization plots.

At 3V, our motor ran at about 968 radians per second, which corresponds to an efficiency of 61.2 percent (depicted in Figure 12). This seemed acceptable to us, since we were operating at 94.4% of the
maximum achievable efficiency at 3V, and the motor wasn’t audibly straining at any point in the step.

To create a steady, yet mobile, 3V power supply, we used two 3V battery packs (each containing two 1.5V AA batteries) wired in parallel. The parallel sources increase the current available to the motor (effectively decreasing internal resistance of the batteries, and stabilizing voltage fluctuations). The extra available current should also (unsurprisingly) extend our emu’s battery life.

Figure 12: A plot of our motor’s efficiency at different angular speeds. Our operating point is indicated by the marker on the blue curve.
To approximate our emu’s battery life (and evaluate the benefit of using four AA batteries instead of two) we can use the operational power output shown in Figure 13 (2.56W). A standard Energizer AA battery contains about 2222 mWh\(^3\) of energy, and could thus supply 2.56W of power (at 1.5V) for about 52 minutes. Our parallel battery

![Power vs. Angular Velocity](image)

Figure 13: A plot of our motor’s power output at different angular speeds. Our operating point is indicated by the marker on the blue curve.

---

configuration will run at 3V for about twice that long; roughly an hour and forty-four minutes. This proved to be more than adequate for the gameday trials.

### 3.2 Power Transmission Efficiency

Since the leg linkages are fairly complicated, it’s difficult to get a nuanced picture of power loss in transmission. However, with a rough estimate of power available at the foot, we can approximate power lost in the transmission as a whole. Power required at the foot to move the emu at a constant speed is a simple function of the emu’s weight and speed (given by equation 5).

\[ P = |F||v|\cos(\phi) \]  

In equation (5), power (P) is described as the dot product of force (F) and velocity (v), with phi representing the angle between the force and velocity vectors (with the velocity vector describing the velocity of the emu’s center of mass). We will assume that the emu’s foot will only exert force in the plane of motion (the y-z plane in the free body diagrams). Equation (5) becomes:

\[ P = |F_z|v_z| + |F_y|v_y| \]  

Coupler point velocity from the working model simulation (running at our operating crank speed) can be used to establish a theoretical velocity for the bird’s foot, and by extension, its center of mass. To simplify the problem, we will divide the emu’s step into two portions: a flat portion, in which the emu is being driven forward, and a vertical portion in which the emu’s body is being driven upwards.
As mentioned earlier in the report, our operational coupler point velocity was predicted by working model to be 0.127 meters per second during the flat part of the step. We used a force plate to measure the tangential force ($F_z$) applied by the emu’s foot during a step. After filtering the data to eliminate noise, we arrived at an average force value of 1.07N. $F_y$ is approximately zero during the flat part of the step, since the motor is not pushing the foot in the $y$ direction. During this part of the step, the configuration of the linkage is such that the normal force on the foot is transmitted to the crank in such a way that the torque on the motor shaft is close to zero (the force is roughly parallel to the crank).

At the beginning and end of the step, the motor is moving the foot almost exclusively in the $y$ direction, and therefore must exert a force ($F_y$) that moves the center of mass upwards. This force will be approximately equal to force of gravity on the emu (it will be slightly higher if you include the force required to provide initial acceleration in the $y$-direction). From the coupler point data presented in section 2.4, we will estimate that $v_y$ for the emu during this part of the step is 0.05 m/sec.

Thus far, we’ve simplified the step into two portions (flat and vertical), and we’ve identified their force and velocity values. However, we haven’t yet taken into account the relative durations of each portion. Using data from Section 2.4, we can estimate that the horizontal part of the step takes about twice as long as the vertical portion. Modifying equation (5) to reflect this feature:

$$P = 0.67|F_z||v_z| + 0.33|F_y||v_y| \quad (6)$$
We can finally plug in our force and velocity values to obtain an estimate for power required at the foot. The numerical results of the calculation are shown below:

<table>
<thead>
<tr>
<th>Fz (N)</th>
<th>vz (m/sec)</th>
<th>Fy (N)</th>
<th>vy (m/sec)</th>
<th>P (W)</th>
<th>E_total (%)</th>
<th>E_trans (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.07</td>
<td>0.127</td>
<td>5.44</td>
<td>0.05</td>
<td>0.181</td>
<td>7.1</td>
<td>11.5</td>
</tr>
</tbody>
</table>

As expected, theoretical power required at the foot is far less than the 2.56W actually output by the motor. The inefficient nature of the transmission is to be expected, since the leg relies on surface contact between linkages to reduce slop. This increased surface contact would be expected to result in significant friction losses.

### 3.3 Force Plate Testing and Analysis

We attempted to measure the normal and propulsive forces of our bipedal robot by using a force plate equipped with capacitive Honeywell FSS force sensors. By having the robot walk over the force plate on one foot, one is able to estimate the walker’s force profiles for the normal force. However, our robot’s feet were too large for the force plate provided. We did the test several times, each time trying to get a cleaner read than the last time, substituting smaller feet and adding shims, but it was not possible for our robot to move across the force plate without our guidance. Our final design exhibits the ability to stand on one foot in Appendix B.2. Naturally, our minimal interference would change the results slightly, but we were able to create graphs of the normal and tangential force profiles over a four second time period as seen in Fig. 14.
These plots display most of the expected characteristics, including shocks at the beginning of the step and directionally consistent measurements. However, inconsistencies in the plots also give us information about the emu’s gait. The normal force plot required significant (~5x) scaling in order to display an average force that balanced the force of gravity on the emu. Clearly, the force plate wasn’t being loaded with the emu’s entire weight, implying that the emu may have dragged its opposite foot while walking. This is supported by observations from slow-motion videos.

3.4 Gameday Performance

Our emu performed exceptionally well on gameday. Relative to the other two robots in our specific heat, our emu managed to pass the 1.5 m mark well ahead of the closest contender. Our emu continued to walk along a straight trajectory over the cobblestones, at an observed speed of roughly 12.35 cm/s, comfortably above the 3 cm/s requirement. In Section 2.4, the theoretical velocity of the body was calculated to be 12.71 cm/s; the slight discrepancy is due to slippage in the feet, frictional forces on the joints, and bumps in the cobblestone. All components of the robot functioned well over both the smooth concrete surfaces, allowing the robot to maintain strong balance and constant forward movement. The feet would occasionally jam on the uneven cobblestone. However, running the emu in reverse avoided this complication entirely, allowing the bird to walk freely over the cobblestones without stalling. On gameday, the Emo Emu was voted by our peers as one of the most biomimetic birds.
Figure 14: Plots of force plate data during a step. Tangential force (top) and normal force (bottom) have been scaled and filtered with a moving average to reduce noise but preserve trends.
4. Bird Redesign

While our current design performed very well, we have identified a few areas of improvement we would implement if provided with the time and resources to go through a full redesign of our emu.

1. Redesign linkages and coupler curve to make the bird take a slightly higher step. This would lessen the amount the bird ‘skates’ across the surface, therefore lessening the interference of the feet when taking a step.

2. Iterate on the coupler curve design in order to increase the amount of time the feet are in contact with the ground, relative to the amount of time they spend in the air.

3. Decrease size of the bird to make it lighter, therefore consuming less power to drive. This would allow for longer battery life, a financial and mechanical advantage.

4. Distribute weight evenly throughout the body. Even weight distribution would prevent the robot from walking on a radial path. Our current design employs a gearbox with an off-center motor, causing the bird to slightly tilt to one side.

5. Redesign the feet to lay flat when in contact with the ground. The load on the feet, due to the forces exerted by the linkages, don’t allow them to lay truly flat. We would redesign the feet to take into account the forces exerted by the legs. This, in turn, would allow the robot to walk better by eliminating the interference between the two feet when in motion.
6. Apply more rubber material to the feet in specific areas in order to minimize slippage and utilize more of the available torque.
Bibliography


Appendices

A. Process Photos

1. Prototype of eventual fixturing system in order to translate axial rotation into planar rotation through a pin joint.
2. Prototype of the linkage system for one side of the bird.

3. Drill pressing steel tubing and acrylic to create rigid crank linkage.
4. Soldering wires from motor to battery pack.
B. Full Prototypes

1. First prototype with angled feet that were eventually substituted for larger feet with 90° angles.

2. Final design standing on one foot.
3. Elegant emu-body design that failed to meet the height restriction of 20 cm. It was later given the bandsaw treatment and parts can be seen on the final design.
C. Plots

1. Plot of motor output torque at different angular speeds. Our operating point is indicated by the marker on the blue line.
D. Matlab Scripts

**Script 1: Used to read force-plate data, extract important values (average forces, etc) and plot the data.**

```matlab
%CONSTANTS
g=9.8;
m=.555;

%====================
%Load data from CSV file, and format it
filename = 'saved_data1.csv';
full_data = csvread(filename,1,0);
F_norm = full_data(:,7);
F_tang = full_data(:,8);
time = full_data(:,1)/1000.0;

%Scale data to meet expectations (using Fn=mg, etc)
F_norm_avg = mean(F_norm);
F_norm_calc = m*g;
correction = F_norm_calc/F_norm_avg;
F_tang_ma = movmean(F_tang,18);
F_tang_corr = F_tang*correction;
avg_tang = mean(F_tang_ma(550:850));

%Plot force-plate data
figure
```

Tf=.000380;
Va=3.0;
Vb=1.5;
m=.1;
Rw =.00125;
FOS = 1.5;
efficiency = .15;

w_nl = 1340.4;
i_nl = .170;
i_stall = 2.32;
o_point = 47*196.7/60.*2*pi
R = 1.5/i_stall;
K = (3-i_nl*R_exp)/w_nl;

%linear vectors of currents between istall and inl
ivector_a = linspace(get_istall(Va, R), get_inl(K,Tf), 100);
ivector_b = linspace(get_istall(Vb, R), get_inl(K,Tf), 100);

w_a = get_w(Va,ivector_a,R,K);
w_b = get_w(Vb,ivector_b,R,K);
```
hold on
plot(time, F_norm);
% plot(time, F_norm_corr);
title('Normal Force vs. Time');
xlabel('time (sec)');
ylabel('force (N)');

figure
hold on
plot(time, F_tang_ma);
% plot(time(550:850),
F_tang_ma(550:850));
title('Tangential Force vs. Time');
xlabel('time (sec)');
ylabel('force (N)');

Script 2: Used to produce motor characterization plots and identify the operating point.

%CONSTANTS==============
PLOT_DATA=1;
plot(w_b, power_b);
plot(o_point,power_a(73),'b*')
display(power_a(73));
title('Power vs. Angular Velocity');
xlabel('w (rad/sec)');
ylabel('P (W)');
legend('3V', '1.5V');

function [Tl] = get_Tl(K, ivector_a, Tf);
Tl_a = get_Tl(K, ivector_a, Tf);
Tl_b = get_Tl(K, ivector_b, Tf);
power_a =
get_power_out(Tl_a, w_a);
power_b =
get_power_out(Tl_b, w_b);

end

function [w] = get_w(V, i, R, K)
inl = Tf/K;
end

if(PLOT_DATA==1)

%PLOT
DATA================
figure
hold on
plot(w_a, power_a);

inl = Tf/K;
end

function [TI] = get_Tl(K,i,Tf)
Tl=K*i-Tf;
end

function [w] = get_w(V, i, R, K)
plot(w_a, eff_a);
plot(w_b, eff_b);
plot(o_point,eff_a(73),'b*')
display(eff_a(73));
title('Efficiency vs. Angular Velocity');
xlabel('w (rad/sec)');
ylabel('Efficiency');
legend('3V', '1.5V');

figure
hold on
plot(w_a, Tl_a);
plot(w_b, Tl_b);
plot(o_point,Tl_a(73),'b*')
title('Torque vs. Angular Velocity');
xlabel('w (rad/sec)');
ylabel('Torque (N m)');
legend('3V', '1.5V');
end

% HELPER FUNCTIONS

function [ratio] = get_ratio(n_torque, stall_torque)
ratio = n_torque/stall_torque;
end
function [n_torque] = necessary_torque(m, Rw, FOS, efficiency)
n_torque =
m*9.8*Rw*FOS/efficiency;
end

function [motor_power] =
get_power_out(Tl, w)
motor_power = Tl.*w;
end

function [istall] = get_istall(V,R)
istall = V/R;
end

function [inl] = get_inl(K,Tf)