Crawler Design Document

ME 112 Winter 2018

Crawler Queens

Katie Plummer, Martina Sly, Kayla Guillory, Elizabeth Price

Mechanical Engineering Design Group
416 Escondido Mall
Stanford University
Stanford, CA 94305-2203

1 Executive Summary

The goal of this assignment was to create a “crawler” out of lego pieces and other approved materials. The crawler was responsible for traveling through a tunnel, grabbing a salamander, and transporting it back through the tunnel, thus training other salamanders on how to use the passage and aiding the species in finding their way to Stanford’s Lake Lagunita.

Our crawler went through many design iterations and prototypes before becoming our final midterm project. Our design was quick on the track and successfully grabbed the salamander by sweeping it up with string and catching it in a small net (Figure 1.1).

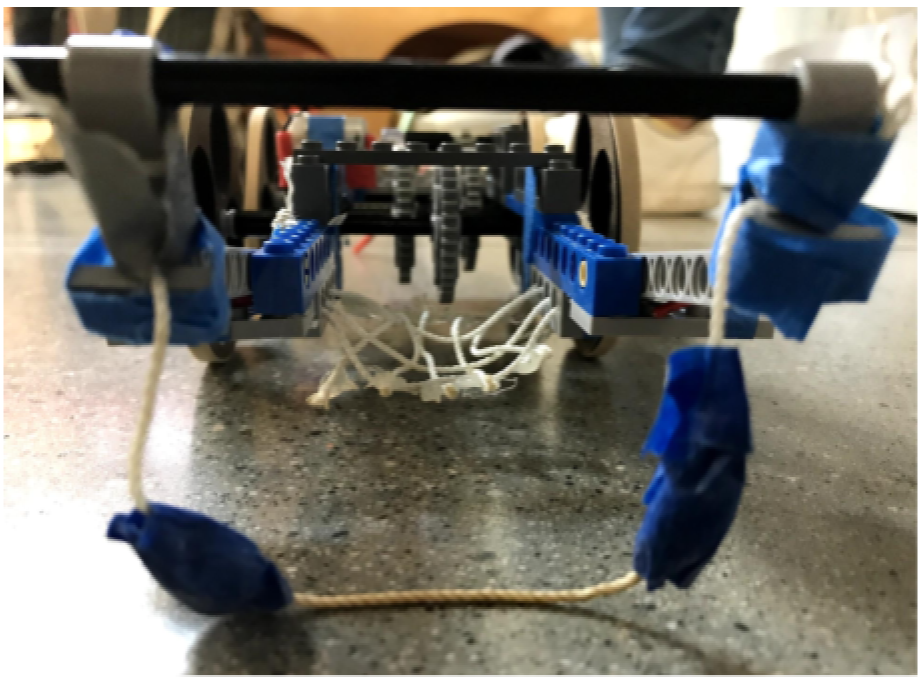


Figure 1.1: *Our final crawler, complete with string catch and net mechanism to capture the salamander.*

As we designed our crawler, we were very conscious of our power output. We began with a 24:1 gear ratio and kept that ratio for most of our design iterations until we found our motor starting to stall and our crawler losing efficiency. We then increased to a 41.7:1 gear ratio, resulting in improved power and efficiency output that put us well below the 10 joule maximum.

We faced difficulties in creating a salamander-catching mechanism, especially because our team wanted to steer away from simply using a sticky surface to capture the salamander. We decided that we wanted to keep the salamander on the ground instead of leaning it on the wall and going against the spirit of the project. These design constraints meant that our mechanism went through a tremendous number of iterations (Appendix A.1). We had many brainstorming sessions to find something that would work. Our final crawler catcher design had weights on either side of a string to ensure that it would scoop the salamander even as it bounced across the gravel. The string slid underneath the salamander's neck and lifted it into a net on the crawler cart. We carefully handcrafted the net to ensure ideally-sized holes to entrap the salamander's legs.

On the track, our design performed well. Our retrieval mechanism failed on the first test, but was successful on the second. We were significantly below the energy constraints, using only 5.98 joules. Our crawler weighed a total of 160 grams, ran at 6.0 volts, and took only 1.8 and 1.9 seconds to traverse the 1-meter track section there and back, respectively.

From this project, our team learned about prototyping, gear ratios and designing for efficiency. Each crawler iteration helped us see what we could do better, and we found that quickly moving through prototypes to improve small problems gave us the best results. Graphs and tables of our motor data also helped us to visualize and improve the efficiency of our design.

Our team hopes to carry what we learned forward to the final project. Not only did we gain insight into performing useful calculations and measurements, we also learned how to function as a team, to adapt plans when prototypes were not performing, and to constructively work through moments of frustration. Combined, our technical and non technical insights will help us create a final project that both functions well and is a great experience to learn and grow from.

Contents

2 Background

The 2018 ME112 crawler project challenged our team to help save the endangered California Tiger Salamander by capturing a salamander and transporting it through a tunnel, training other salamanders on how to use the under-road passage. A successful design was measured by the ability of the crawler to travel to the end of the passage, obtain the salamander, and carry it back to the beginning of the track while using a limited amount of energy.

Fig. 2.1: View looking down the track, a model for the tunnel under Junipero Serra. Note that this track had gravel and bumps on the floor during testing.

Fig. 2.2: The salamander we set out to rescue.

One initial design constraint was the size of the tunnel, a 2-meter long channel with a 13.5 cm x 9 cm rectangular cross section and a slope created by a 5 cm vertical rise over the length of the track. Additionally, our device could not be over 30 cm long, had to operate at either 3.0, 6.0, or 8.0 volts when running, draw less than 2.0 Amps. Furthermore, our energy usage, as calculated by multiplying our time, voltage, and current over a 1.0 meter stretch there and back, had to be below 10 Joules. We were given an approved list of materials to work with.

Based on the design constraints, our group decided that it would be most realistic for the scenario to try and capture the salamander on the ground instead of propping it up against the back wall. We felt this was the most accurate interpretation of the prompt. We also decided early on that we would rather try to use a creative catching mechanism to obtain the salamander, as opposed to just sticking the salamander to something. With these additional constraints we knew we had our work cut out for us.

3 Design Description

The Crawler Queens crawler came together by combining several design decisions into one vehicle that could successfully accomplish the salamander retrieval challenge without exceeding the energy requirements. Our pivotal crawler design elements include the front-wheel drive, the salamander retrieval mechanism, our gear transmission, and the wheels.

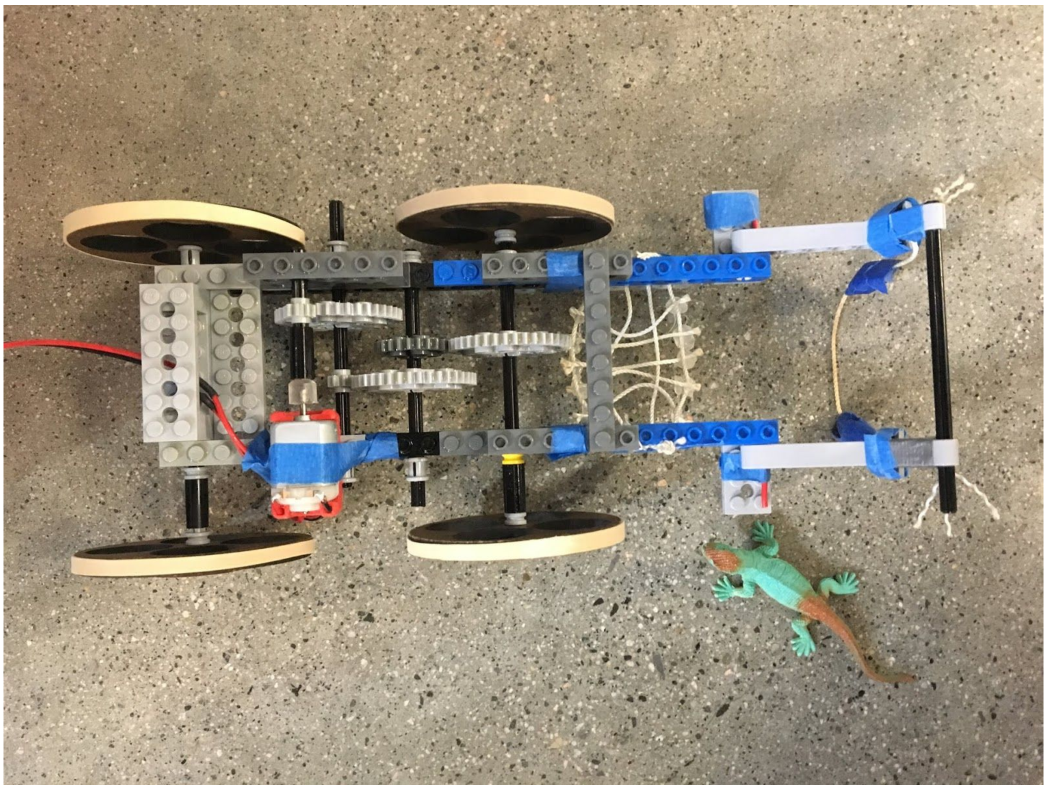


Fig. 3.1: Top view of crawler

3.1 Getting Across the Track

One of the first design elements our group implemented was front-wheel drive. As we began prototyping for the crawler drive system, front-wheel drive seemed like the obvious starting point. We tested our crawler with different gear configurations and gear ratios. We began questioning our choice of front-wheel drive after settling on our initial gear ratio of 1:24.

To ensure front-wheel drive was the best choice we decided to simultaneously test alternatives and perform research on when front-wheel drive is preferable. Our rear-wheel drive test failed when our crawler could not surmount the first step on the wooden track; we realized our crawler needed the torque at the front-wheels provided by front-wheel drive. The all-wheel drive test worked, but the increase in energy loss due to friction and the slower speed of the crawler convinced us that this was not a good alternative to front-wheel drive. Plus, the increase in traction that four-wheel drive provides was unnecessary considering our two-wheel system was not having much trouble with slipping at that point. Looking deeper, the results of these experiments lined up with what we had learned through research: front-wheel drive is better in cases like ours, where the bulk of the car's weight is over the front wheels. The forward weight pushed the crawler down at the front and helped the driving wheels find traction in the gravel.

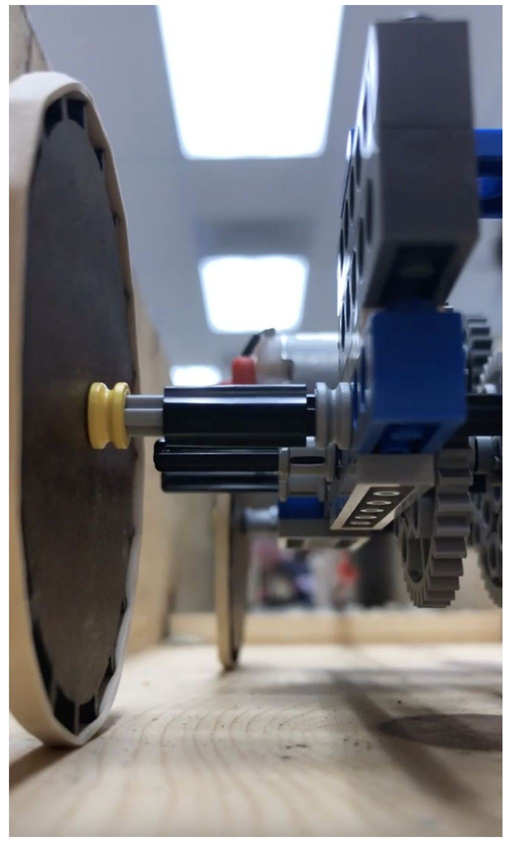


Fig. 3.2: Front view of our crawler on the track. This is a midpoint prototype so you can see wheels with teeth.

Initially, our crawler was more dramatically unbalanced in terms of weight distribution; the center of gravity was almost directly over the front wheels. However, after more design iterations, the distribution ended up being closer to the midpoint between the wheels. This helped our crawler handle better and improved its balance as it traversed the track. Overall, we did not have many stability issues, but after multiple iterations, we changed our wheels to help curb some of the intense bouncing on gravel.

3.2 Acquiring the Salamander

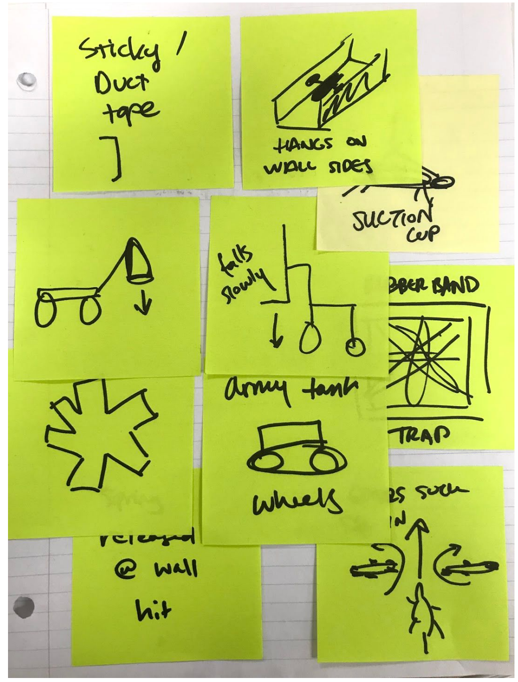


Fig. 3.3: Several design ideas as the result of a brainstorming session on how to capture the salamander.

Our salamander acquisition method went through many prototypes and our group was constantly brainstorming new ways to improve upon what we had. We determined that we had to solve two separate, but related, problems: 1) the acquisition of the salamander, and 2) the safe transportation of the salamander. We reached an elegant solution to the challenge that maintained the spirit of the competition by scooping the salamander up from the ground and gently transporting it.

Since we were determined to lift the salamander from the ground, we faced the challenge of designing a scooping mechanism that could lower to the ground but would not crash into the barriers while the crawler was driving. We solved this problem by testing flexible materials (Appendix A.1) that dragged along the ground and slid underneath the salamander in the end zone.

The first design we came up with was a scoop that rotated downward toward the ground as the crawler moved forward, scooping the salamander at the end of the track when it was fully rotated, but not scooping up rocks during travel. This design required an additional gear train, and after we tried a few versions with a worm gear, we abandoned the idea in favor of a mechanism that did not require its own gear train, thus increasing gear train friction and decreasing our efficiency. We also considered a rubber-band catch, other string-related ideas and, briefly, a sticky wall before we arrived at our final design.

Our final design consisted of a length of string that hung down to the track at the frontmost section of the crawler. On either side of the string were two rocks taped in, acting as weights. The string was also attached to two “L” shaped bars that rotated freely. As the crawler approached the salamander, the string slid under its neck, and when the crawler hit the wall, the “L” shaped bars were forced upward and over, bringing the salamander with them. This solution also went through many design adjustments, including the shortening of the entire crawler to avoid exceeding the 30-centimeter length restriction, a modification that also decreased our crawler’s weight.

To solve the second problem, the transport of the salamander, we needed a design that safely entrapped the salamander while allowing free movement of the salamander scooping mechanism. We tested rubber bands, sticky tape, lego platforms, and more (see Appendix A.1). We settled on a section of carefully constructed handmade netting. The spacing of the netting was designed such that once just one limb was trapped in the net, the salamander could be transported back to the beginning of the track.

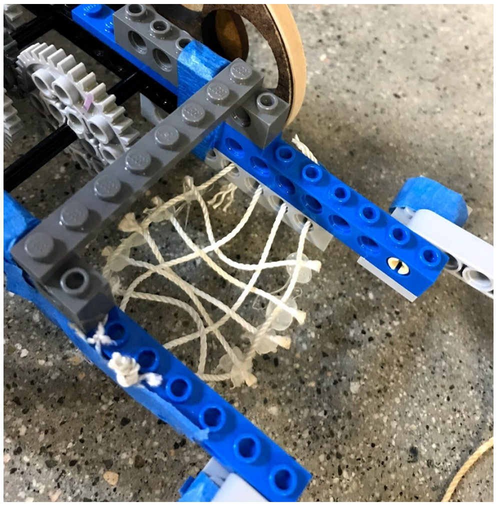


Fig. 3.4: A close up of our handmade netting to hold the salamander on the crawler.

In returning to the beginning of the track there were only a few differences for our crawler. First, the front-wheel drive became a rear-wheel drive. Due to the front-heaviness of our crawler combined with rear-wheel drive, the first bump the crawler had to traverse on the way back caused a huge bounce for the crawler and would often toss the salamander out of the catching mechanism in early prototypes. Our net was a direct response to this problem and kept the salamander trapped, even over the bump. We also found that our crawler typically moved faster when returning with the salamander, likely due to the fact that it was moving downhill.

3.3 Gear Ratios

Our initial focus in designing our crawler was on our energy efficiency. We quickly arrived at a lightweight, fast-moving, 2-wheel drive crawler that sped over the gravel and had sufficient torque to surmount the barriers. However, once we began testing crawler catching and transporting mechanisms, we realized that the added weight required additional torque. Consequently, we added another gear stage and transitioned to our final gear.

We decided to switch our gear ratio from 25:1 to 41.67:1 because it seemed that our car was using more energy than necessary, and our motor was close to stalling. Although the crawler was running very quickly over the gravel, the current was higher than desired (about 0.4 Amps). By adding another gear stage, we decreased the amount of current needed to run the car and the amount of torque necessary at the motor for the crawler to run. With this new gear ratio we were able to run at about 0.26 Amps while still maintaining a fast speed over the gravel, greatly reducing our energy use.

Although we knew the additional gears would add friction to our gear train, we suspected that the trade off would be worth it and our improved efficiency reflects that hypothesis. With our 41.67:1 gear ratio we were able to run closer to peak efficiency. In figure 3.5.1 and 3.5.2, you will see the change we made with the gear ratios on our crawler.

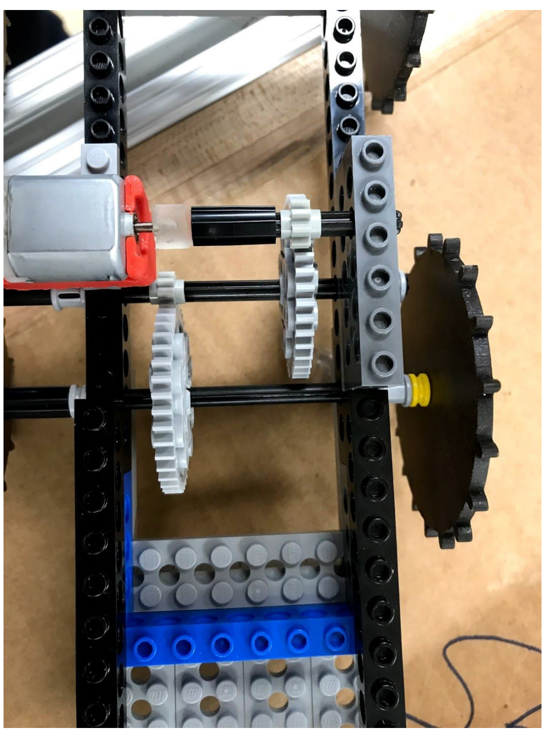


Fig. 3.5.1: A view of our first transmission.

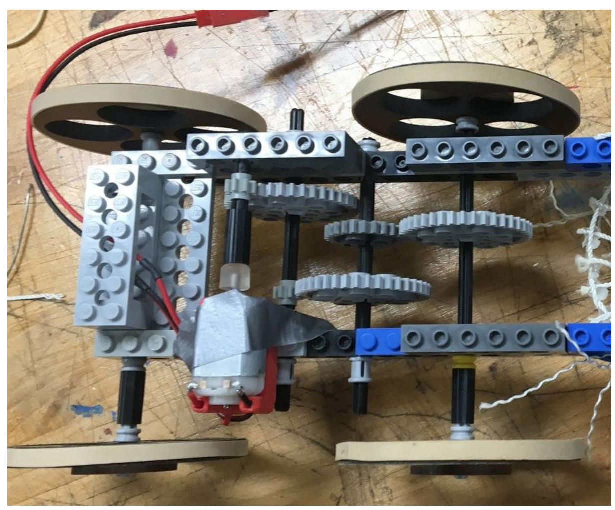


Fig. 3.5.2: A view of our second transmission.

3.4 Wheels

The wheels of our crawler proved to be an interesting design challenge considering there were fairly few limitations on the shape and size we could make. We started with four foam core wheels as quick and dirty prototypes. The foam core wheels were unreliable and had little traction compared to the laser cut wheels we ultimately used. The foam core wheels were roughly 6 centimeters in diameter, because we thought large wheels would help with stability and surmounting obstacles, but we wanted to maintain good efficiency with smaller wheels, so 6 seemed like a good middle range place to start.

Fig. 3.6: Our first laser cut set of wheels. The small teeth were not good for reliability.

The first set of laser-cut wheels we made were 1/8th inch thick and had many small teeth around the outside (see figure 3.6). Because the duron wood material used to make these wheels was fairly slippery by itself, we also made the decision early on to put rubber bands around the outside. These wheels were a great step toward a more functional crawler and gave us a much better idea of how effective our gear train was; however, we noticed a few features we wanted to change.

During the second iteration of wheels we decided to try 1/4th inch thick duron. We were uncertain if having more weight on the car in future iterations would help or hurt our crawler so we prototyped two new sets of wheels, one with holes cut out and the other without. The choice of a round shape instead of toothed exterior was made in order to increase reliability of the rubber bands that were constantly slipping off the teeth of our first set.

Fig. 3.7: The second time around we prototyped two sets of round wheels, one set with holes to reduce weight.

We ended up using the lighter wheels with holes in them to reduce the weight of the car, a choice we were happy with once we saw the high speeds our crawler was achieving. The wheel diameters ended up at 7 centimeters, a number we settled on after deciding to go up a little from the original foam wheels, but waiting to be cautious about upper bounding height restrictions (the tunnel was 9cm high). Our caution was warranted as our final scooping mechanism rose above the height of our wheels, so we were lucky to have given ourselves room for error. However, the larger wheels were essential for surmounting the bumps on the track, so we are also lucky we did not go smaller in diameter.

3.5 Final Improvements on Efficiency

In addition to some of the bigger design choices we made to create the most efficient crawler possible, we also made a few small adjustments that we believe further improved our efficiency. Once we settled on our gear ratio, capturing mechanism, weight/weight distribution, and overall design, we adjusted the fit of the gears and added olive oil. Gear adjustment was done by loosening shaft collars and adjusting the height of the motor to improve the meshing of gears. Olive oil was applied anywhere there might have been friction.

3.6 Logistics

Our final design was reliable in its ability to start smoothly, surmount the first barrier, and travel across the gravel terrain. We simply had to plug the leads into the power source running at 6 volts to get the crawler to travel to the end of the track, and then reverse them for it to return. The momentum of the crawler would force the "L" shaped lego parts used in the catch mechanism upward when it hit the wall, a main reason why our crawler's high speed was an advantage.

The one part of our logistics that was occasionally difficult was the acquisition of the salamander. In practice, our salamander scooping mechanism was often successful as part of our forward movement to the end of the track. However, if our initial attempt was unsuccessful, we had to reverse the leads and reverse the crawler to the last part of the "end zone," then reverse the leads again and go forward for a second attempt at picking up the salamander before reversing a final time and returning to the start of the track. This was the only special procedure our crawler occasionally required for reliable operation.

4 Analysis of Performance

In this section we will discuss our overall speed ratio and efficiency. The figure below shows a diagram of the losses in efficiency in our crawler. In our crawler design, we identified and characterized three stages of power transmission. First, electrical power was converted into mechanical rotation of the drive shaft. Then, our transmission connected the motor axle to the drive wheel axle in three stages with a speed reduction of 41.67:1. Lastly, the crawler used the rotation and torque of the wheel axle to turn the wheels for track traversal. Inevitable losses were experienced at each stage, so in order to maximize efficiency we calculated and analyzed the power losses of our crawler.

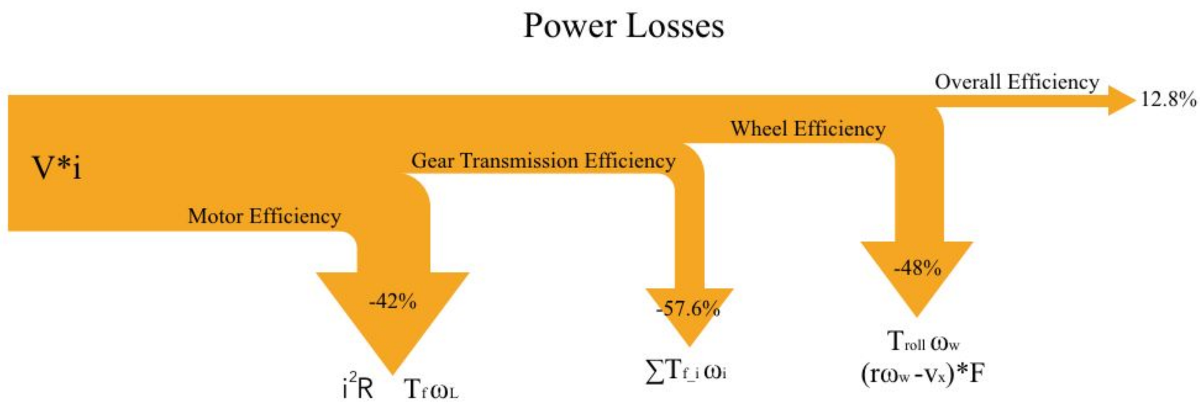


Fig. 4.1: A diagram showing crawler power losses. Efficiency of each process has been modeled and analyzed.

4.1 Motor Efficiency

To calculate our motor efficiency analysis, we began by running multiple tests. We expected two sources of efficiency loss in the motor's conversion of electrical power to mechanical power. The first source came from the fact that the motor had some internal resistance. The second source was the motor shaft which experienced some forces in opposition to its motion. The following equations, derived from Kirchoff's law and the Lorentz force model to the motor circuit, allowed us to characterize our motor:

$$V - iR - k\omega = 0 \qquad (1)$$
$$Ki - Tf = Tl \qquad (2)$$

Where V = voltage, i = current, k = the electromagnetic constant, Tf = friction torque, Tl = output load torque, and ω = angular velocity in radians/second.To find the variables R, k, and Tf (assuming these will stay constant), we ran stall and no-load experiments on the motor.

For our stall measurements, the angular velocity, ω, was zero so we could find the the motor resistance using equation (1). We ran the motor at increasing voltages while holding the motor shaft so that it could not spin. We then recorded the current coming in through the power supply. With 10 different voltages and their respective currents, we observed a motor resistance, R, of about 7.9 Ohms.

For the no-load measurements, the output torque, Tl, is zero. The motor was able to rotate freely. Using equation (1) with V, inl and ωnl measured, and R obtained from the stall test, we could solve for k. We tested different voltages, recording their respective currents from the power supply, and measured the ω with a tachometer. With the multiple voltages, we were able to calculate an average k value of 0.004197 Nm/Amp. From equation (2), we know that tl is zero and therefore Tf is equal to k*i. From the experimental values, we got a Tf value of 0.0001704 Nm.

Once we had measured all the necessary constants, we could produce plots of power, efficiency, torque, etc. as a function of current or speed for any operating voltage.

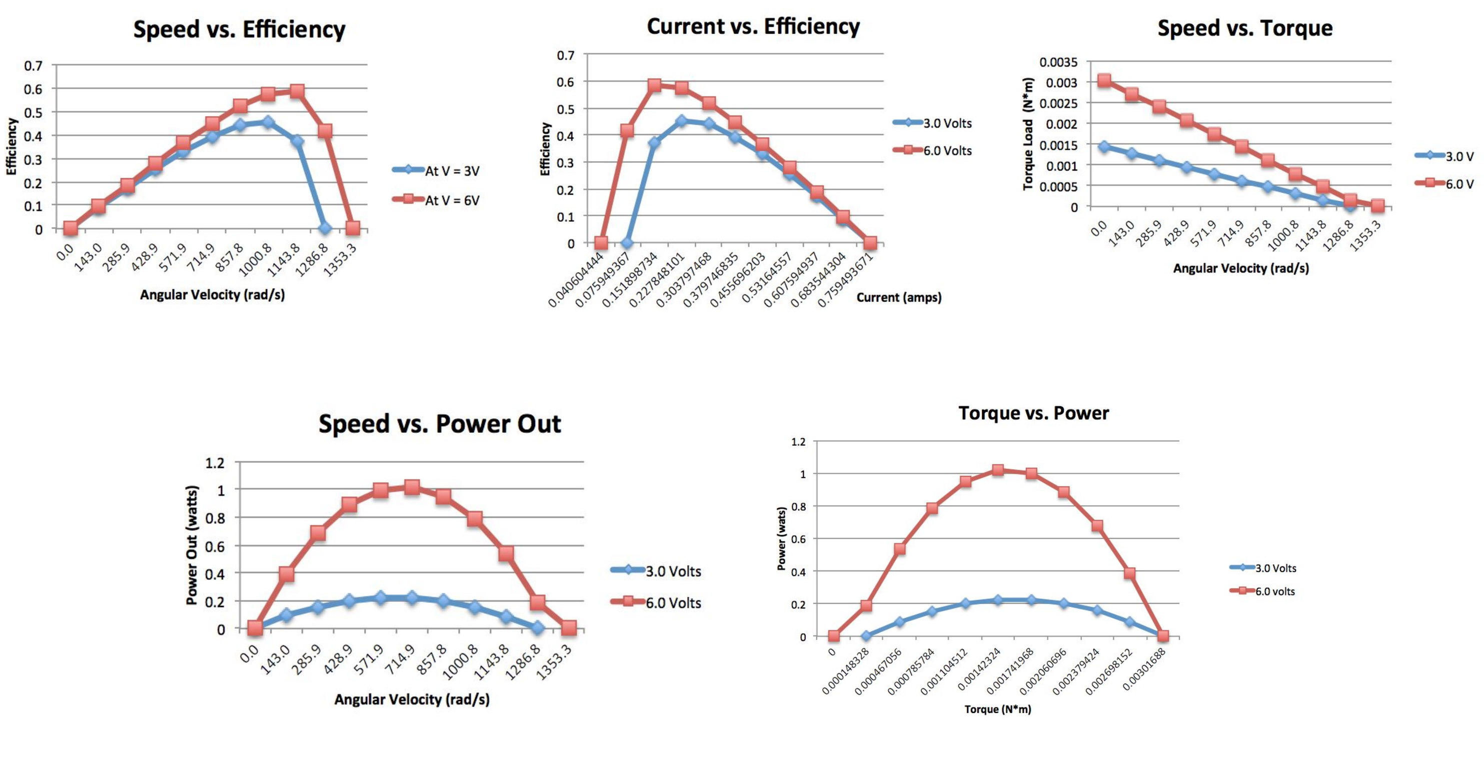


Fig. 4.2: These five graphs show plots of power, efficiency, torque, etc. as a function of current or speed for any operating voltage

Analyzing the Current vs. Efficiency graph even further, we noticed that we were not running at an efficiency that was satisfying. Our crawler required too much current to get down the track. We decided to increase our crawler's gear ratio from 25:1 to 41.67:1 and found that this significantly reduced the input current that our crawler was experiencing from about 0.40 Amps to about 0.27 Amps. With this change, our motor efficiency really improved, as seen below.

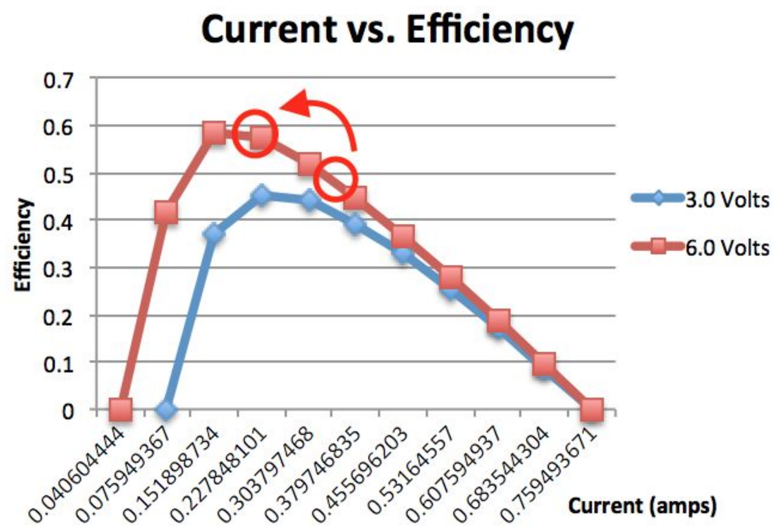


Fig 4.3: The red circles show the efficiency increase from our first transmission to our second.

4.2 Gear Transmission Efficiency

We determined our gear transmission efficiency by performing a test to determine our actual torque output as compared to the 100% efficiency torque output as calculated in our Python code (Appendix A.3). To run this test, we elevated our crawler such that the wheels were not touching the ground and attached a pulley with a cup with variable weight in it to the front wheel drive shaft (Figure 4.4). We ran the motor at 6.0 volts and determined the weight at which the current reading was equivalent to our competition runs (0.26 amps), which turned out to be 44 grams. We used that weight to calculate the force and torque on the pulley, and the actual torque output at the wheel normally (Appendix A.2).

Fig 4.4: Gear transmission efficiency test setup

We compared that actual torque output to the expected torque output with 100% efficiency to determine the combined efficiency of the gear train and the motor, then solved for the efficiency of the gear train itself, 42.4%. This efficiency could be improved; in previous ME 112 labs our team had achieved efficiencies of up to 70% for lego gear trains. Perhaps the number of stages (three) in our gear train, or imperfect gear meshing, impacted our gear train efficiency. We did have difficulty adjusting the motor to the correct height to mesh with the second gear, which likely added friction.

4.3 Wheel Efficiency

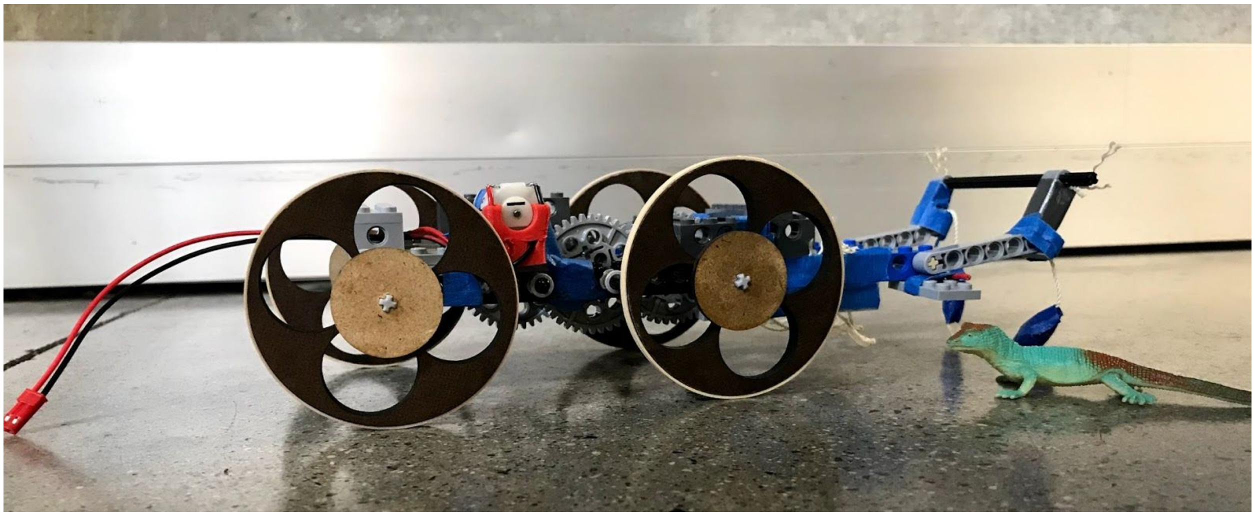


Fig 4.5: Side view of crawler

In order to understand how our wheels were affecting our efficiency we decided to test the slippage of our wheels on the gravel. We timed and filmed our crawler traveling 1.0 m on gravel and 1.0m on flat ground and determined the number of rotations of the drive wheels. We then calculated the theoretical distance the crawler should have traveled from the number of rotations and determined its theoretical and actual speeds (see Appendix A.2). We compared these speeds to one another to determine the velocity efficiency loss due to slippage, a 48% loss on gravel and a 6.6% loss on flat ground. While the gravel value is higher than we would like, our slippage decreased significantly throughout the project. With our gear-shaped wheels (see Appendix A.1), the slippage was visible to the naked eye, while with our final circular wheels it was not noticeable.

Although the slippage calculations above took the rolling friction of the wheels into account, we calculated the value of this rolling resistance using free body diagrams to help inform our design decisions during the project.

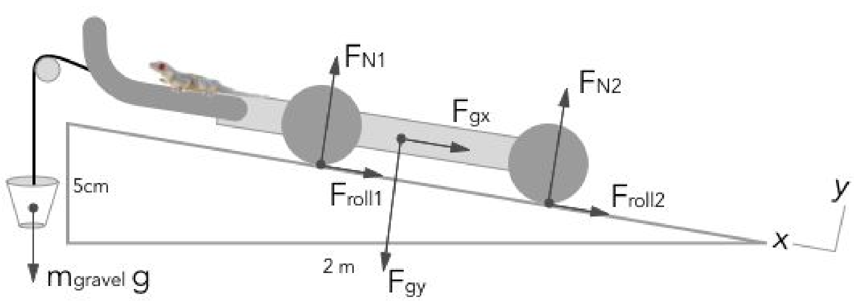
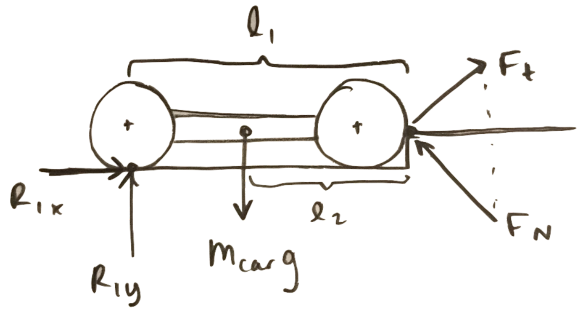


Fig 4.6: Free Body Diagram showing the crawler on gravel as it just begins to be pulled by a cup filled with a certain amount of gravel.

We modeled the rolling resistance as a force opposing the direction of motion by attaching our crawler to a string and pulley with a cup of gravel hanging on the other end (see FBD Figure 4.6 above) and allowing the cup to pull the crawler. We found the amount of gravel in the cup required to begin moving the crawler. We measured the weight of the cup and used it to find the rolling friction force (see A4) using the equation below.

$$\Sigma F_x = F_{roll1} + F_{roll2} - m_{gravel}g = 0$$

Another useful Free Body Diagram we analyzed was the front wheel of the crawler right before it surmounted the first barrier. This represented a worst-case torque scenario for our crawler, because the crawler lacked the momentum it would normally have from approaching the obstacle with speed. By summing the forces and moments of the diagrams below we found the torque required for our car to surmount the bump. This process helped us see how our center of mass was affecting our crawler's performance. We had to move the center of mass back on the crawler at one point because the weight of the salamander-scooping mechanism caused the crawler to occasionally tip forward. However, our analysis showed us that we shouldn't place the center of mass right at the midpoint of the crawler because biasing the weight toward the front wheels was actually helping the vehicle over the first bump. As previously mentioned this center of mass adjustment improved the reliability and handling of the crawler, but still made passing over the bump easier than it would have been if the center of mass was in the direct center of the crawler body.



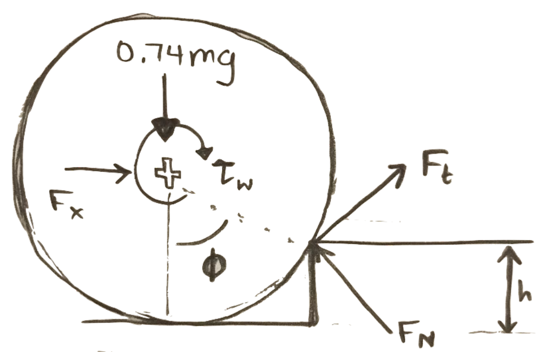


Fig 4.7: Free Body Diagrams showing the moment before the crawler surmounts the first track barrier.

4.4 Strength Analysis

We used Python to solve for the Lewis-AGMA bending stress of each gear (see Appendix A.3). The largest stress was on gear 3, likely due to its small number of teeth, its distance from the motor, and therefore its exposure to increased torque. Gear 3 underwent 91.7 psi of bending stress, a very safe value for Lego gears, which have an ultimate strength of about 5000 psi and an allowable adjusted stress of 3500 psi. Thus, we did not need to be highly concerned about a strength failure of our gear train.

Table 4.1: Lewis AGMA Stress for Each Gear in Pounds per Square Inch

Gear Number	Number of Teeth	Lewis-AGMA Bending Stress in psi
1	8	13.9
2	40	7.5
3	8	91.7
4	40	49.6
5	24	88.9
6	40	80.0

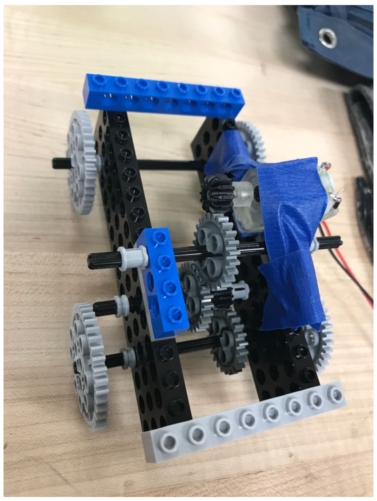
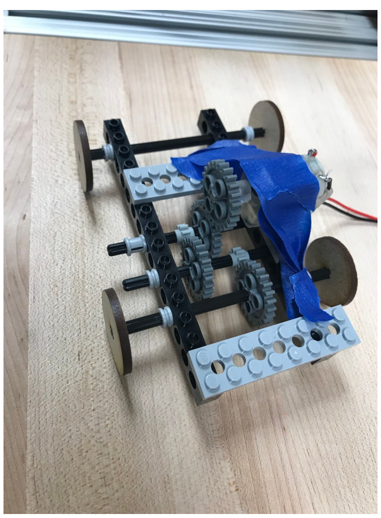
5 Conclusion

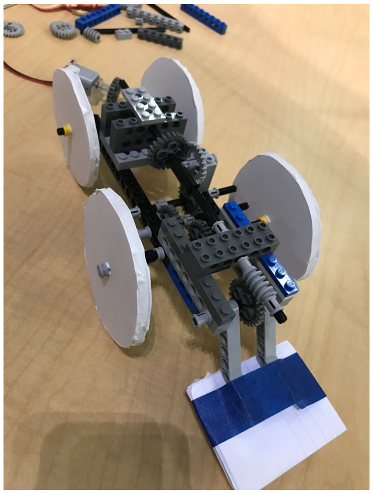
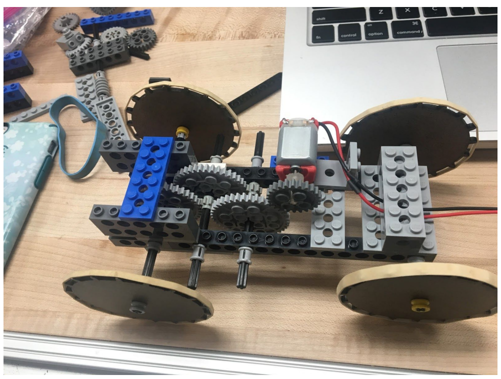
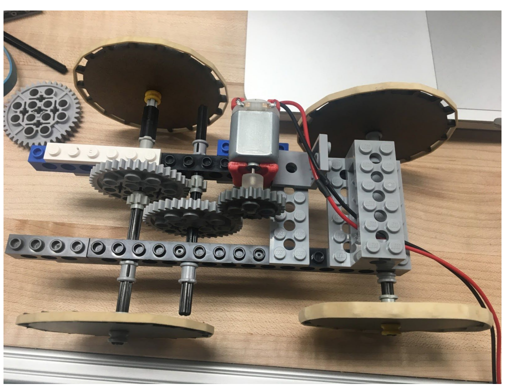
Our crawler design allows for generalization. When asked by a researcher if our crawler could save the California Tiger Salamanders, we would make a few changes and share with her a more powerful crawler capable of transporting a heavier salamander. One change we would certainly make would be moving the center of mass further back on the crawler. Our center of mass is currently pretty close to the front wheels, and having a heavy salamander in the netting on the return leg would likely tip our crawler over. Depending on the exact weight of the salamander, we might also have to increase our gear ratio further to give our crawler the extra torque to transport the salamander. One simple way of doing this would be to replace our 5th gear, the 24 tooth one, with an 8 tooth gear, increasing our overall gear ratio to 125:1. We might also have to increase our power supply to 8.0 volts to account for the added weight. Finally, we might have to use a material stronger than string for the salamander scooping mechanism and net. We would experiment with different materials and test the strength of our current string to determine if it would be capable of supporting a heavy salamander.

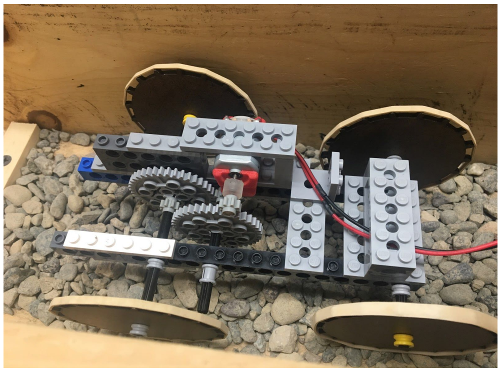
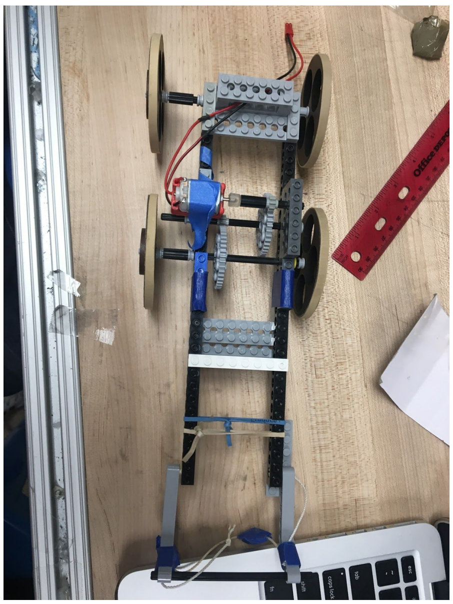
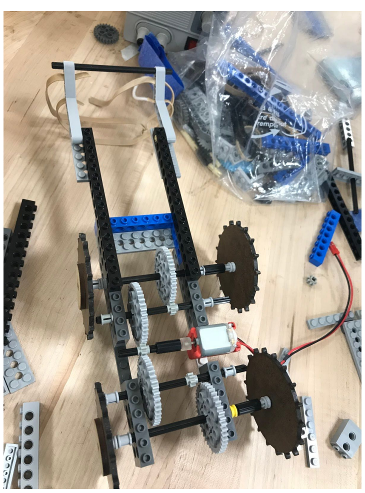
When all is said and done, we are immensely proud of our crawler and the job we did! We were able to safely transport the salamander and crawler across the tunnel. In comparison with the rest of the class in terms of energy use, we were way below the average. The class average energy use was 7.94 Joules, while our team managed to complete the task using only 5.98 Joules. We are confident that our crawler runs quickly and efficiently across the gravel. Our salamander retrieval method did not always work as expected due to salamander placement, crawler placement and incoming speed variations, but overall it was mostly reliable. Some changes we might make would be to design a better salamander trap that will be 100% effective. Some changes that could be made going forward to increase the efficiency of our crawler would be to reduce the weight and friction, increase gear ratio slightly, or attempt to increase the transmission efficiency. By doing this, we would reduce the required motor torque, which reduces current draw at 6 volts. In our case, increasing our gear transmission efficiency and wheels efficiency would be most effective. Gear transmission efficiency could be made better by making sure gears are meshing properly and possibly reducing the number of gear trains (although this would take away from the motor efficiency). To improve on our wheel efficiency, we could try smaller wheels, or a different wheel design. With this being said, we were able to successfully retrieve the salamander with only 5.98 Joules of energy and reached our design goals. We may have saved the entire salamander species!

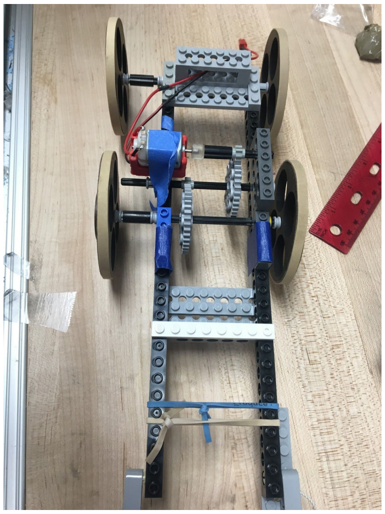
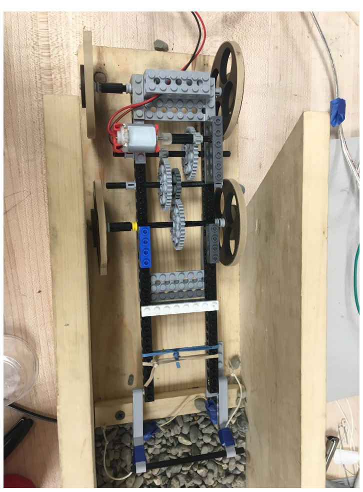
A Appendices

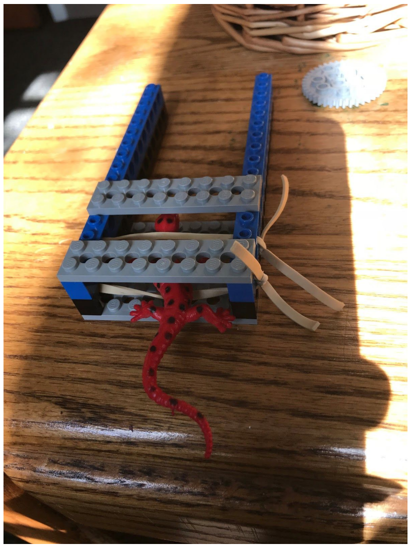
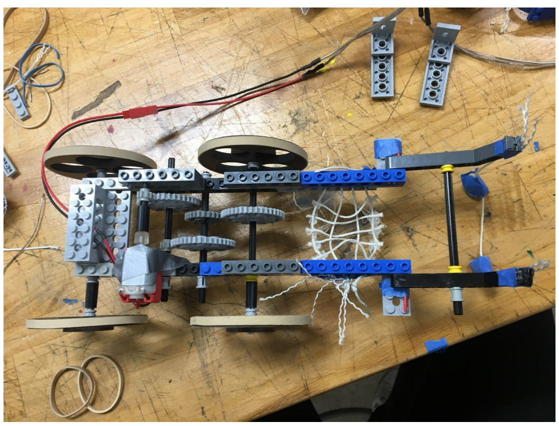
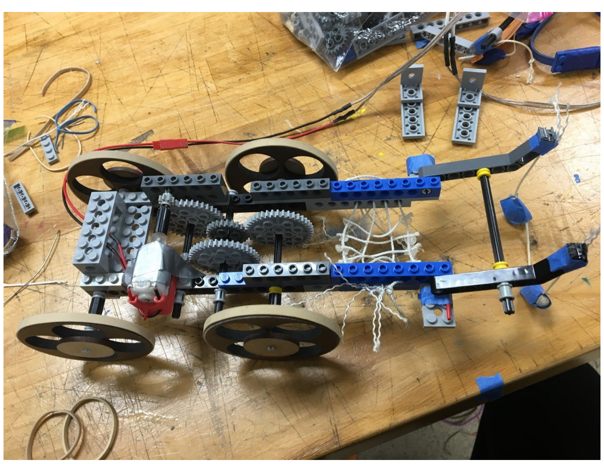
A.1 Prototype Modeling

Model	Features
	**<u>Prototype 1</u> - 10pm 2/1/18** ● 12:24:12:24 + idler: overall gear ratio of 4:1 ● Cart moves on flat surface at 2.0 V with small laser cut and 40 tooth gear wheels ● Does not move on gravel (tried up to 6.0 V) ● Attempt a higher gear ratio for more torque
	**<u>Prototype 2</u> - 2/1/18** ● 8:24:8:24: (9:1 overall ratio) ● Ran on gravel (not well) at 2.5-3.0 V ● Ran on flat surface at 0.9-1.3 V, 0.1 A

	**<u>Prototype 3</u>** ● Thinking about using bigger wheels to allow more room for gears, higher suspension, and potentially better traction ● Implemented a possible salamander retrieval mechanism that is directly powered by the motor and given a 24:1 gear ratio by use of the worm gear ● Crawler didn't move even using 9V
	**<u>Prototype 4</u> 2/5/18** ● 24:40:8:40:8:40 (41.67 overall ratio) ● New wheels ● Ran on gravel at 3.0 V ● Started using a new motor because we realized the old motor was not working properly (amps reading was about 2 when there was no load)
	**<u>Prototype 5</u> 2/5/18** ● 24:40:8:40 (8.333 overall ratio) ● NOT enough torque to move over gravel

	**<u>Prototype 6</u> 2/5/18** ● 8:40:8:40 (25:1 overall ratio) ● Worked on gravel at 3.0V, fast speed
	**<u>Prototype 7</u>** ● 8:40:8:40 (25:1 overall ratio) ● New salamander retrieval mechanism that doesn't rely on motor
	**<u>Prototype 8</u>** ● All-wheel drive 2x8:40:8:40 ratio ● Worked on gravel at 4.0V, decent speed ● Tried this ratio+voltage to see 4-wheel drive would be a better option than front-wheel drive ● Widened chassis so that motor is no longer cantilevered (to decrease force pushing up on motor)

	**<u>Prototype 9</u>** ● Front-wheel drive; 8:40:8:40 (25:1 overall ratio) ● New wheels without spokes to decrease slippage ○ Additionally, spokes were too small, and prototyping new spokes that were the correct size would be time consuming
	**<u>Prototype 10</u>** ● Weighted the rubber band to that it would be in the proper place to pick up the salamander
	**<u>Prototype 11</u>** ● Increased the gear ratio to improved efficiency and torque with the added weight of crawler transporter and picking up mechanisms ● We added another stage (24:40) to increase the gear ratio ● Gear ratio: 8:40:8:40:24:40 (41.7:1 overall ratio)

	**<u>Prototype 12</u>** ● Same gear ratio, changed picking up salamander mechanism to two straight rubber bands on the front of the car to hook salamander. ● Did not work because the height of the rubber bands could not be low enough to trap salamander without hitting gravel or ground bumps.
	**<u>Prototype 13</u>** ● Same gear ratio, changed picking up salamander mechanism again. ● Back to swinging with string. Added two rocks to provide weight to keep the string down. ● Changed the landing pad to a net instead of rubber bands
	**<u>Prototype 14</u>** ● Same gear ratio, same mechanism for picking up and holding salamander ● Shortened body of crawler to meet 30cm-maximum length requirement

A.2 Efficiency Calculations

A.2.1 Slippage:

Gravel:

Theoretical distance it should have traveled:

$Revolutions\ *\ \pi *\ diameter\ = 8.5\ revolutions * \pi * 0.072\ m\ =\ 1.92\ m$

Actual distance traveled: 1 m

Theoretical speed: 1.92 m / 2.55 s = 0.753 (m/s)

Actual speed: 1 m / 2.55 s = 0.392 (m/s)

Loss due to slippage on gravel: 0.753 - 0.392 (m/s) = **0.361 m/s loss**

0.361 (m/s) / 0.753 (m/s) = **48% slippage efficiency loss**

Ground:

Theoretical distance it should have traveled:

$Revolutions\ *\ \pi *\ diameter\ = 4.75\ revolutions * \pi * 0.072\ m\ =\ 1.07\ m$

Actual distance traveled: 1 m

Theoretical speed: 1.07 m / 1.54 s = 0.695 (m/s)

Actual speed: 1 m / 1.54 s = 0.649 (m/s)

Loss due to slippage on gravel: 0.695-0.649 (m/s) = **0.046 (m/s) loss**

0.046 (m/s) / 0.695 (m/s) = **6.6% slippage efficiency loss**

A.2.2 Gear Train Efficiency Calculations

$T_{out}\ =\ Force * radius\ =\ (0.044\ kg\ *\ 9.8\ m/s^2)\ *\ 0.041\ m\ =\ 0.0177\ N * m$

$T_{predicted}\ =\ 0.0529\ ft * lbs\ =\ 0.0718\ N * m$

$0.0177\ (N * m) / 0.0718\ (N * m)\ =\ 24.6\%\ efficient,\ efficiency\ loss\ of\ 75.4\%$

However 24.6% includes the efficiency lost in the motor; we must solve for the gear train efficiency:

Motor and transmission efficiency = Motor efficiency * Gear train efficiency

Gear train efficiency = Motor and transmission efficiency / Motor efficiency

Gear train efficiency = 24.6% / 58% = **42.4%** (lose 57.6%)

A.3 Python code for Lewis-AGMA adjusted bending stress for each gear

```
# Face width (feet)
b = 0.01

# Pitch (feet)
P = 25.38071

# Num of gear teeth for each gear
n1 = 8
n2 = 40
n3 = 8
n4 = 40
n5 = 24
n6 = 40

#speed ratio
spr = n2/n1 * n4/n3 * n6/n5

# max stall current in Amps
Istall = .759

#current while running in Amps
i = .26

#Tf in ft-lb (constant)
Tf = 0.00012568

#k in ft-lb/Amps (constant)
k = 0.003095

#Resistance of motor in Ohms (constant)
R = 7.9

# Torque Input (or TL)
Tin = k*i-Tf

# Max stall torque
Tstall = k*Istall-Tf

# Pitch radius of each gear (in feet)
pr1 = 0.009186
```

```
pr2 = 0.06135
pr3 = 0.009186
pr4 = 0.06135
pr5 = 0.03510
pr6 = 0.06135

# Outer radius of each gear (in feet)
or1 = 0.01608
or2 = 0.06824
or3 = 0.01608
or4 = 0.06824
or5 = 0.04232
or6 = 0.06824

# Tangential force & torque
ft1 = Tin / pr1
ft2 = ft1
t2 = ft2 * pr2
t3 = t2
ft3 = t3 / pr3
ft4 = ft3
t4 = ft4 * pr4
t5= t4
ft5 = t5 / pr5
ft6 = ft5
t6 = ft6* pr6

 # Shock and overload factor
ko = 1.3

# Mounting factor
km = 1.6

# Quality factor
Qv = 10

# Angular Velocity (rpm) of gear 1
av1 = 8192

# Velocity gears 1 & 2 (ft/min)
Vt12 = (pr1 * 2 * (math.pi)/ 12) * av1

# Angular velocity
```

```
av2 = av1 / 5
av3 = av2
av4 = av3/5
av5 = av4
av6 = av5/1.66667

# Velocity gears 3 & 4 (ft/min)
Vt34 = (pr3 * 2 * (math.pi)/ 12) * av3

#Velocity gears 5 & 6 (ft/min)
Vt56 = (pr5 * 2 * (math.pi)/ 12) * av5

# Use A and B for calculate kv (velocity factor)
B = ((12-Qv)**(2/3))/4
A = 50 + (56*(1 - B))

kv12 = ((A+(Vt12)**(1/2))/A)**B
kv34 = ((A+(Vt34)**(1/2))/A)**B
kv56 = ((A+(Vt56)**(1/2))/A)**B

# Lewis geometry factors, J
J1 = 0.20
J2 = 0.37
J3 = 0.20
J4 = 0.37
J5 = 0.36
J6 = 0.40

# Pressure angle
phi = 20

# Center distance
C = pr1 + pr2

# Addendum radius of gears
ra1 = (n1 + 2)/(2*P)
ra2 = (n2 + 2)/(2*P)
ra3 = (n3 + 2)/(2*P)
ra4 = (n4 + 2)/(2*P)
ra5 = (n5 + 2)/(2*P)
ra6 = (n5 + 2)/(2*P)

# Base radius of gears
```

```
rb1 = (pr1*math.cos(phi))
rb2 = (pr2*math.cos(phi))
rb3 = (pr3*math.cos(phi))
rb4 = (pr4*math.cos(phi))
rb5 = (pr5*math.cos(phi))
rb6 = (pr6*math.cos(phi))

# Base pitch
Pb = ((math.pi)*math.cos(phi))/P

# Contact ratio
CR12 = (((ra1**2) - (rb1**2))**(1/2) + ((ra2**2) - (rb2**2))**(1/2) - C*math.sin(phi))/Pb
CR34 = (((ra3**2) - (rb3**2))**(1/2) + ((ra4**2) - (rb4**2))**(1/2) - C*math.sin(phi))/Pb
CR56 = (((ra5**2) - (rb5**2))**(1/2) + ((ra6**2) - (rb6**2))**(1/2) - C*math.sin(phi))/Pb

# Lewis-AGMA adjusted bending stress for each gear in pound-force/square foot
sigma1 = (ft1 * P * ko * km * kv12)/(b * J1)
sigma2 = (ft2 * P * ko * km * kv12)/(b * J2)
sigma3 = (ft3 * P * ko * km * kv34)/(b * J3)
sigma4 = (ft4 * P * ko * km * kv34)/(b * J4)
sigma5 = (ft5 * P * ko * km * kv56)/(b * J5)
sigma6 = (ft6 * P * ko * km * kv56)/(b * J6)

# Stress for each gear in Psi
sigma1_psi = sigma1 * 0.00694444
sigma2_psi = sigma2 * 0.00694444
sigma3_psi = sigma3 * 0.00694444
sigma4_psi = sigma4 * 0.00694444
sigma5_psi = sigma5 * 0.00694444
sigma6_psi = sigma6 * 0.00694444
```

A4 Analysis Calculations

$Cup + Gravel\ needed\ to\ pull\ car\ =\ 40g$

Calculation of F_{roll}

$\Sigma F_x = F_{roll1} + F_{roll2} - m_{gravel}g = 0$

$F_{roll} = (0.04)(9.81)$

$F_{roll} = 0.39\ N$

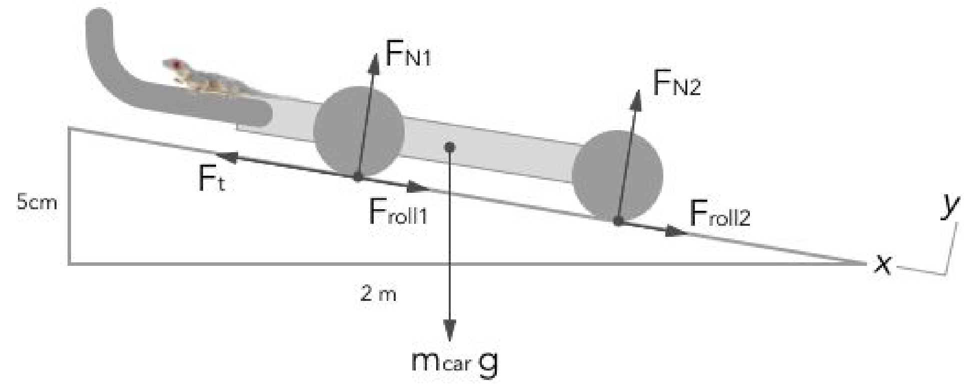


Fig A4.1: Full crawler Free Body Diagram

Calculations for F_t

$F_t - F_{roll} - m_{car}g * sin(\theta) = 0$

(from equation above $F_{roll} = 0.39\ N$)

$F_t = (0.39N) - (0.16)(9.81) * sin(1.43°) = 0$

$F_t = 0.35N$

Calculations for Wheel Torque

$T_\omega = F_t * r_\omega$

$T_\omega = (0.35) * (0.036)$

$T_\omega = 0.0126\ Nm$

Torque

$F_t = F_{roll} + m_{car}g * sin(\theta)$

$T_\omega = F_t * r_\omega$

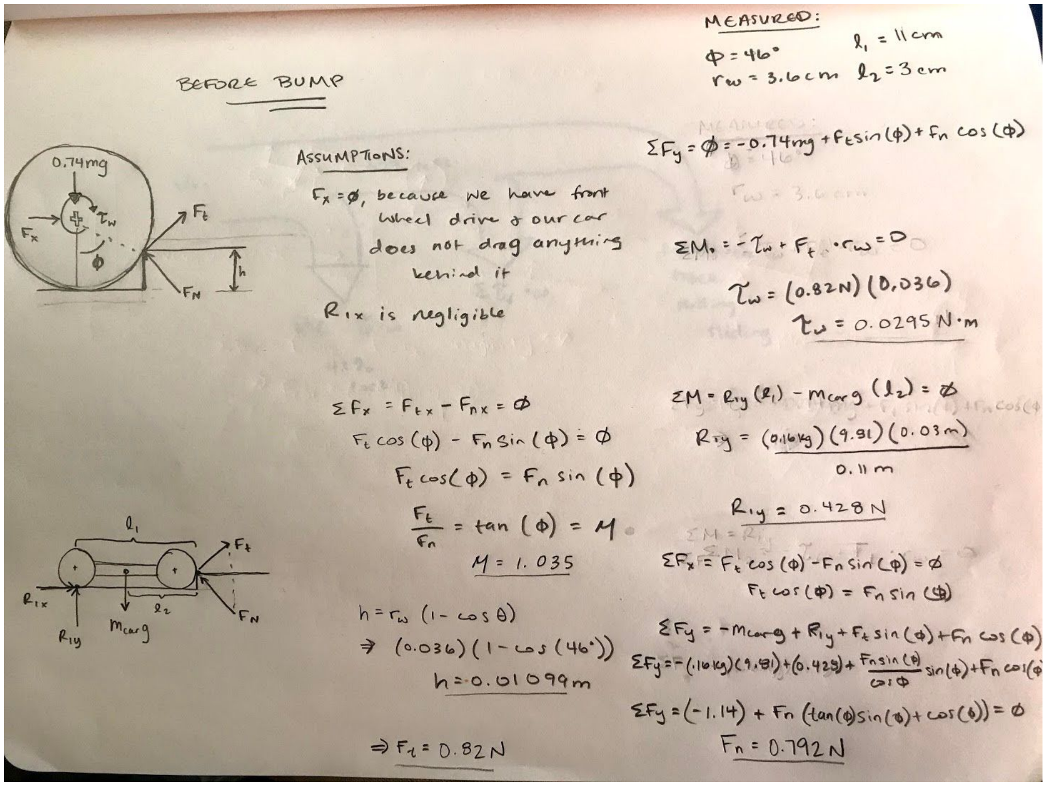


Fig A4.2: Hand written calculations for Free Body Diagram based wheel analysis.