✓MRC

Crawler Design Document

ME112

Team Jurrasic Four

[redacted]

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1 Executive Summary

For this project, the challenge was to create a small lego machine that could descend a track (which models a lava tube), grab a package (modeling a protoceratops egg) and ascend the track with as little energy expenditure as possible. Factors such as such gear ratio, crawler length/width, oil usage, tire selection and gear selection were all taken into consideration during the design phase, in which our group played with multiple designs in order to optimize efficiency of the machine.

nice

Our final design, shown in Figure A.2, resembles a drag racer with power being delivered to ~~what would be~~ the back wheels. The long-bodied design helps balance the moment of the crawler when a 100 gram egg is in the collector at the most down-hill edge of the crawler. The mechanism for retrieving the egg is a rubber-band-loaded rolling arm, which rotates on a pivot in order to roll up the ledge on which the egg is placed and push it off the ledge. This mechanism has never failed. The transmission has a speed reduction of 180, and operates near 30% efficiency. The crawler can stop and stay motionless in the tube under no power input due the the inclusion of a worm gear in the transmission. The gear ratio and efficiency allow~~s~~ the motor to run at currents very near its peak efficiency, outputting around 58% of the input electrical power. Some energy is lost to rolling resistance, which our tests indicate result in 9% power losses. We found losses to tire slippage to be negligible.

@ what voltage?

We calculated our crawler's total theoretical efficiency to be (15.5%). Based on our design calculations, we predicted an energy expenditure of 10.2 J. In testing, the total energy expenditure was 8.3 J, which corresponds to an efficiency of (17.8%). This energy expenditure is well under the desired value of 12 J.

Great Summary

Cool. Looks like truck is driving over it :)

Figure 1.1: *An Epic Picture of our Crawler, named Cradle Robber*

Contents

2 Background

Inspired by the new Jurassic Park movie to soon be released and the unfortunate circumstances that always seem to occur during movies of the type, the goal of this project was form teams to create a small machine that would save an egg that a dinosaur laid. The egg needed saving because it was laid in a lava tube at the top of the park's volcano, the heat of which would kill the baby dino minutes after hatching. We needed to make a device that could descend the tube, safely retrieve the egg and ascend the tube with the egg, all in under 5 minutes. But that's not all; due to ~~the~~ complications with the electric fencing around the park and the possibility of the mother getting angry and ruining the escape (since she doesn't realize her baby will die here), the machine can't use more than 9V of energy and can't reach 36 Joules/meter (ideally 12 J/m). If these conditions are successfully met, our machine will be able to stealthily descend, grab the egg and ascend so that everyone ends up happy and alive. The final requirement is to make sure the machine does not resemble an oviraptor, as the mother will most likely freak out, break the machine, and go on a rampage that would destroy the park.

& fumes

3 Design Description

The key features of the design of our crawler are the body, the transmission, the egg-retrieving mechanism, and the linear guides. All of these features come together and interplay in our crawler design, allowing our team to quickly and efficiently retrieve the protoceratops egg from the lava tube.

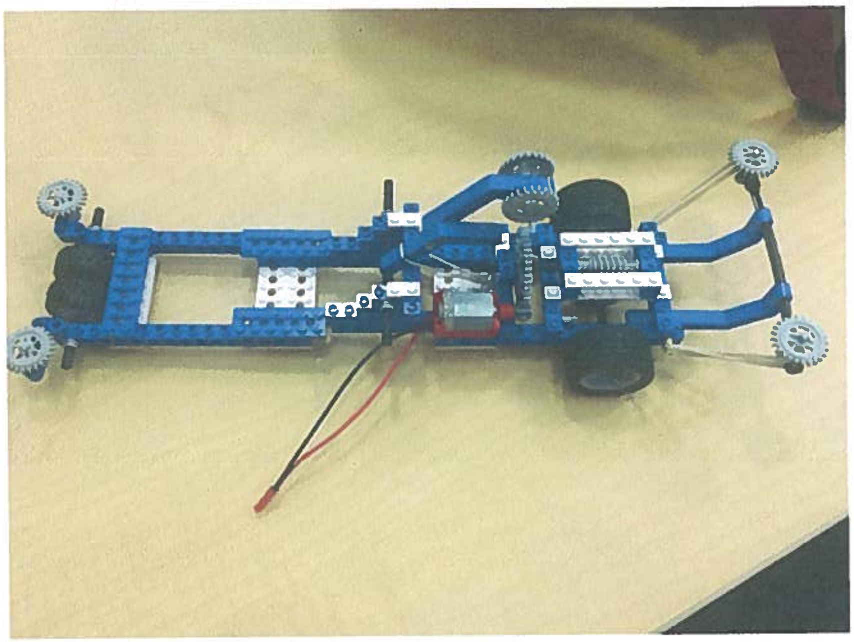


Figure 3.1: *Top Left View.*

?

3.1 Crawler Body

The body of the crawler is over 30 cm long, spanning 27 cm between the front and rear axle. The length of the body serves two purposes - one of balance and another of efficiency.

As shown in 3.2, our crawler collects the egg in a basket-like structure that extends beyond the downhill wheels. This design makes collection simple, as the crawler can simply use its arm to push the egg of the back of its ledge onto the collector. The drawback is that the egg creates a large destabilizing moment that tends to lift the uphill end of the crawler off the ground, causing the back end to drag on the ground. This happened during a few tests before we finalized the body of the crawler, and the total energy expenditure when ascending the tube in the tipped position was only about 20% higher than with pure rolling - still an unnecessary loss of efficiency. The long-bodied design allowed us to increase weight near the uphill wheel by a small amount (such as adding a second front wheel) in order to stabilize it. 20 grams of mass at the front of the crawler 27 cm in front of the downhill axle can stabilize a full 100 gram egg 5 cm behind the downhill axle.

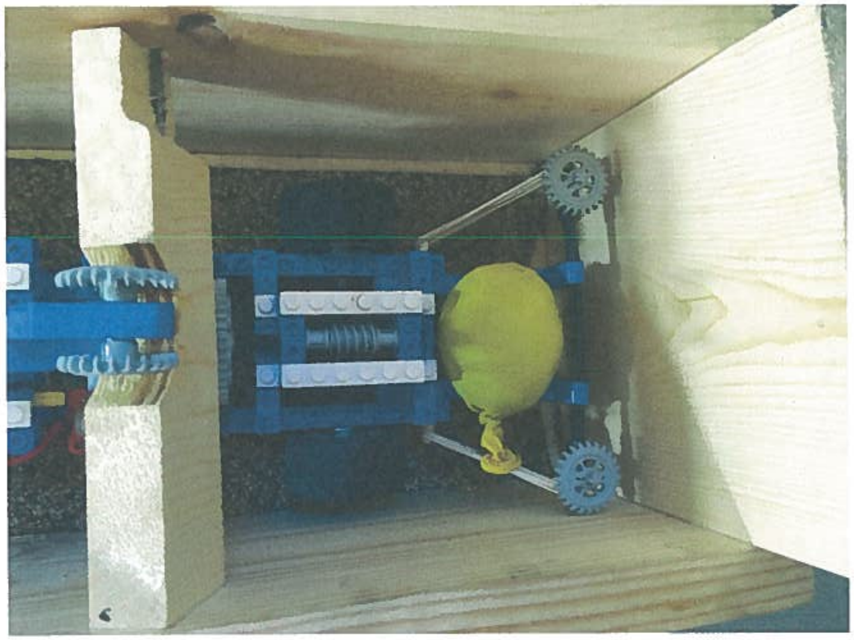


Figure 3.2: *The collector loaded with the egg at the bottom of the tube.*

Although the total energy expenditure was only calculated for ascending one meter of track, the energy expenditure of the entire trip is very important when rescuing protoceratops eggs. Our long-bodied design, when placed with the uphill wheel at the top end of the track, has to travel less total distance than another crawler of lesser length, which will cut down on total energy expenditure and time.

So, 0.5m long crawler?

3.2 Crawler Transmission

The final transmission, shown in Fig. 3.3, of our crawler has a gear ratio of 180. This speed reduction occurs through two stages: the first is a 5x speed reduction from an 8-tooth pinion to a 40-tooth gear, and the second is a single start worm gear to a 36 tooth gear that rotates the drive axle (which is the downhill axle). ✓

We made the decision early in the design process to use a worm gear to ensure that the transmission was non-backdriveable and could therefore stop easily both on the descent and ascent. The large speed reduction during a single stage is also an attractive feature, though it comes at a small efficiency cost over achieving the same reduction with only spur gears.

The total gear ratio we used for our transmission is a result of both theoretical and experimental evidence. Once we characterized our motor, we knew what the output torque (at the current for peak efficiency) would be for any given voltage - see A.1. We also knew what the force required to run the crawler would be (assuming no losses) once we estimated a mass. With this knowledge (and the radius of our back wheels), we determined what the

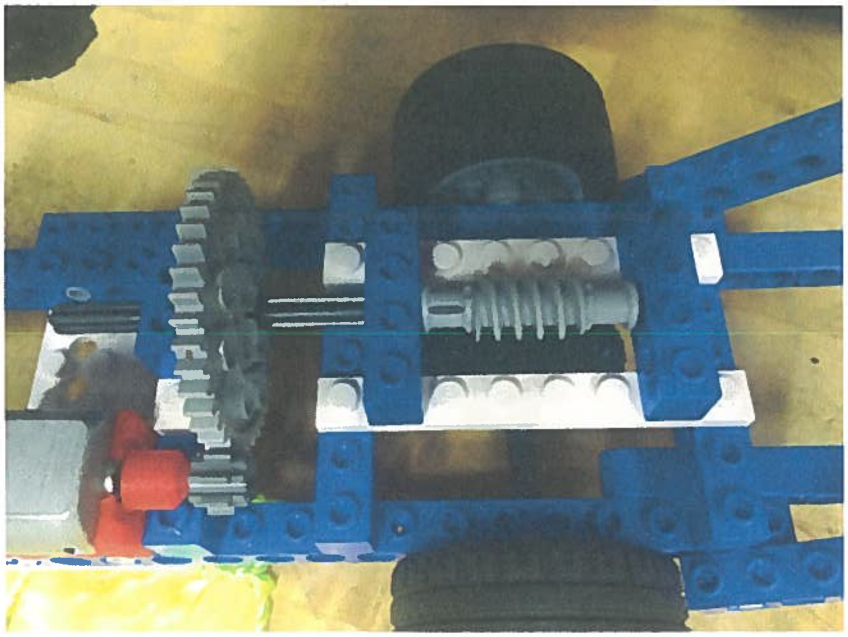


Figure 3.3: *Crawler Transmission.*

gear ratio would need to be to run the crawler at peak motor efficiency with no losses in the transmission. The following equation relates T_L, the load torque out of the motor, and the gear ratio: $T_L(GR)(\eta_{gt}) = (m_{crawler} + m_{egg})g\sin(\theta)r_{wheels}$. The load torque at current for peak efficiency can be found with A.4, A.3, and A.2 in the Appendix. To solve for gear ratio, we modified the previous equation to get:

4.0x10^-4

$$GR = \frac{(m_{crawler} + m_{egg})g\sin(\theta)r_{wheels}}{T_L\eta_{gt}} \tag{3.1}$$

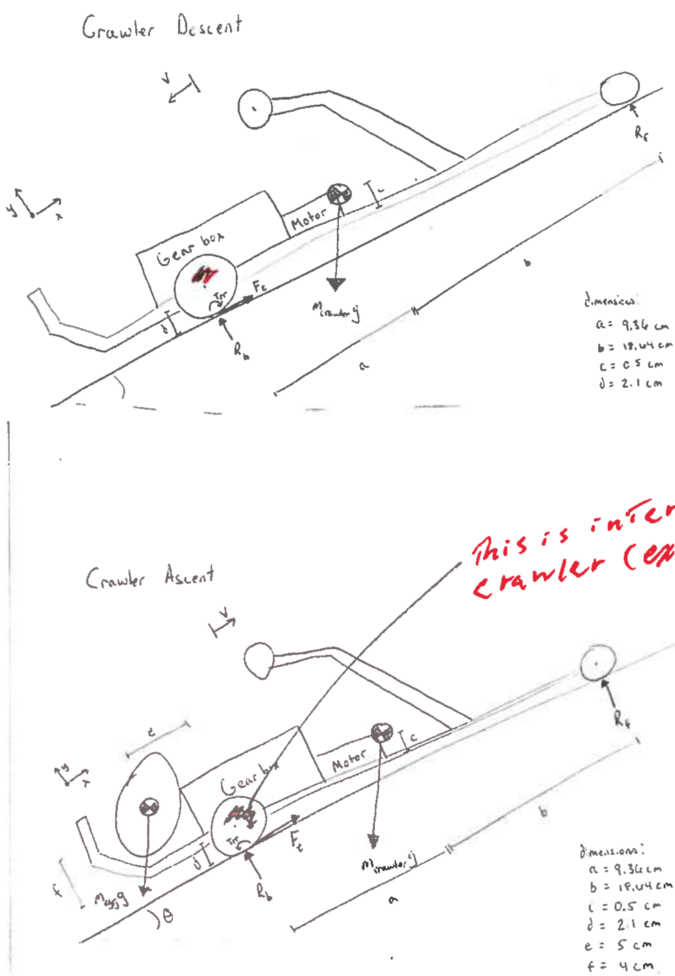
Knowing our drive wheel radius to be 2.1 cm, our motor output torque at 8V to be about .0004Nm (depending on angular velocity), and estimating 300 grams total ~~weight~~ mass and some transmission efficiency on the order of 50%, we calculated that a gear ratio near 150 would best suit our needs.

Based on the available gears and their best meshing pairings, the first gear ratio we tried was 120. ~~not 150.~~ This choice exhibited some behaviors that were not ideal, as it was drawing a higher current than the current for peak efficiency. ~~and~~ Moreover, the efficiency was highly volatile based on small changes in the lego fittings. In order to reduce the current to more efficient levels, we developed a similar but more robust transmission with a gear ratio of 180, which runs at 0.18-0.22 amps under 8 volts of electricity, right in the range for peak efficiency.

The downhill axle of the crawler receives power from the transmission. This was a simple decision, because the majority of the weight is distributed onto the downhill wheels, especially when the crawler is loaded with the egg (see Fig. 3.4). We found virtually no slippage during our tests, which affirms that driving these wheels is the correct decision.

Use leading zero

How did you find this?



I would put equations from section 5.2 here for completeness, then refer back to them from that section.

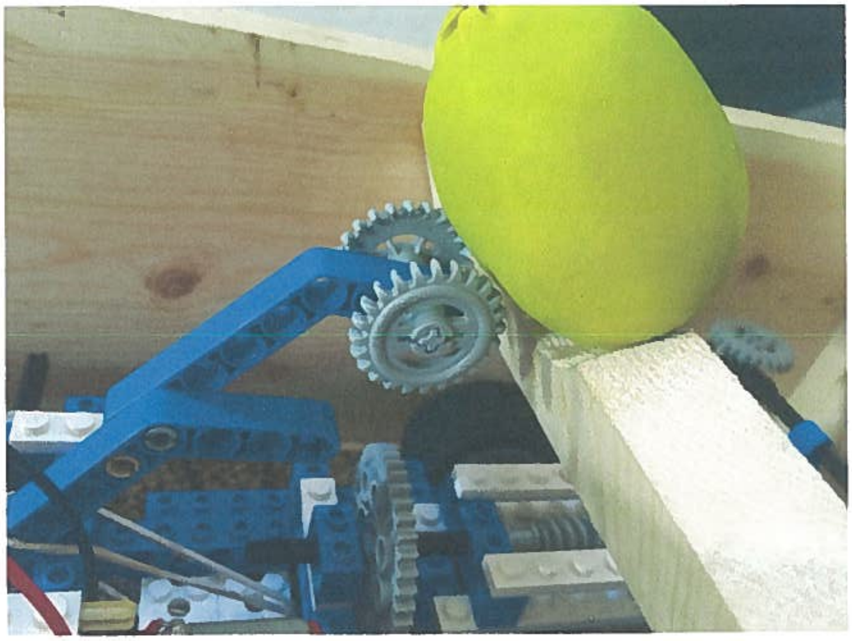
This is internal to crawler (external to wheel)

Figure 3.4: *Free Body Diagram of the Crawler descending and ascending the tube. Weight distribution biased toward drive wheels in order to minimize the chances of losing traction.*

3.3 Egg Retrieval Mechanism

The egg-retrieving mechanism figure is incredibly simple, but has proven to be 100% effective thus far. We discussed and constructed many other, often much more complicated designs, before coming up with the ~~the~~ current pushing mechanism.

The arm, which is lightly loaded by a rubber band in order to give it the ability to rotate, has a set of rolling gears on the end. These gears are at a height such that, when the crawler nears the bottom of the track and the collector is protruding beneath the ledge on which the egg sits, they will begin to contact the ledge. As the crawler moves slightly more downhill, these gears roll up the ledge as the arm rotates and push the egg off (Fig. 3.5). The rubber band is loaded such that it has plenty of force to push off the egg, but the force of the crawler moving down the track allows the arm to bend back in order for the gears to roll up the ledge.



nice!

Figure 3.5: *Retrieval mechanism pushing the egg off of its ledge.*

The collector takes up the space behind the gearbox (see Fig. 3.2), using rubber bands to provide side walls. We designed the collector to be as light as possible to maintain the stability of the crawler on ascent. Its effective width is nearly the entire track. This ensures that, no matter what angle the egg is pushed off the ledge at, it will land in the collector.

3.4 Linear Guides

In order to ensure that the crawler would not stray sideways an rub up against the sides of the tube, our design includes linear guides (shown in Fig. 3.6 and 3.7) made of free-rotating gears that will roll against the wall if they make contact. The normal force against the wall keeps the crawler running straight with minimal friction losses.

We used small gears on the downhill end and large gears on the uphill end in order minimize the moment below the drive wheels and maximize the balancing moment in front of those wheels. Both linear guides and increased uphill mass where needed in our design, and this solution satisfies both problems.

ok

The total width of both the uphill and downhill guides is only a little smaller than the width of the tube. This design ensures that the crawler follows a fairly straight path that minimizes energy expenditure and time. On the other hand, the guides are not the full width of the tube in order to allow the crawler to run freely in the center of the tube without any additional losses in the ideal case, which is what actually occurred during the official testing day.

lots of nice attention to detail!

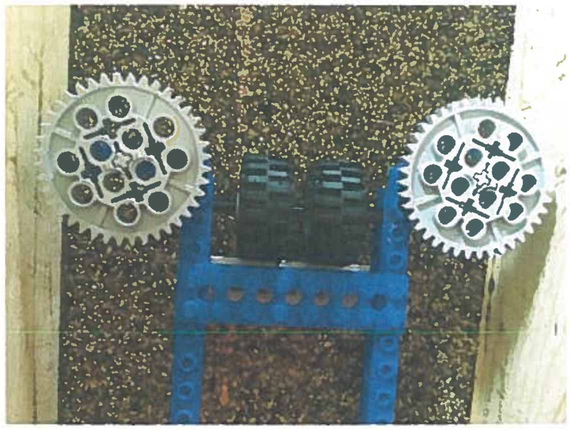


Figure 3.6: *Uphill Linear Guides*

Figure 3.7: *Downhill Linear Guides*

3.5 Logistics of Egg Retrieval

The logistics of our plan for egg retrieval are not complex. Due to the simple linear nature of the test track, our options are limited to a downward approach, and displacement of the egg into a receiving structure on the crawler. With this would method in mind, the task became to design and implement a mechanism that both 1) reliably displaced the egg from rest, and 2) didn't interfere with crawler motion.

In our final mechanism the gears give the tool enough area to minimize force absorption by the egg, while the pivoting action allowed the tool to apply an element of the force in the horizontal and vertical direction. As mentioned above, force applied in just the horizontal direction was counteracted by friction, but an element of this force being applied vertically from under greatly reduced the contact force and friction between the egg and wood. With this reduced friction, the horizontal element is more than enough to displace the egg. Finally, the gears on the end of the prod serve a very useful second purpose; when the crawler starts ascending, the prod is easily able to roll off the wood and back into place, with no problems getting stuck. This ensures the mechanism didnt interfere with the crawlers return progress.

4 Analysis of Performance

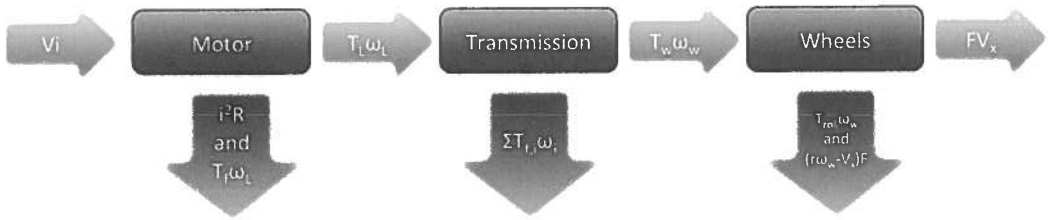


Figure 4.1: *Power flow through crawler system. At each stage of power transmission, the system experiences losses, which we have modeled and predicted in our efficiency calculations, as well as measured in various tests.*

In our crawler design, we identified and characterized three stages of power transmission. First, our motor converted electrical power into mechanical rotation of its shaft. Second, our transmission coupled the rotation of the motor axle to the drive axle, introducing a speed reduction of 180:1 in two stages. Finally, the crawler converted the rotation and torque of its axles into translational power up and down the lava-tube through its wheels. None of these stages is perfectly efficient, and as a result we faced the challenge of characterizing, calculating and minimizing the losses at each stage.

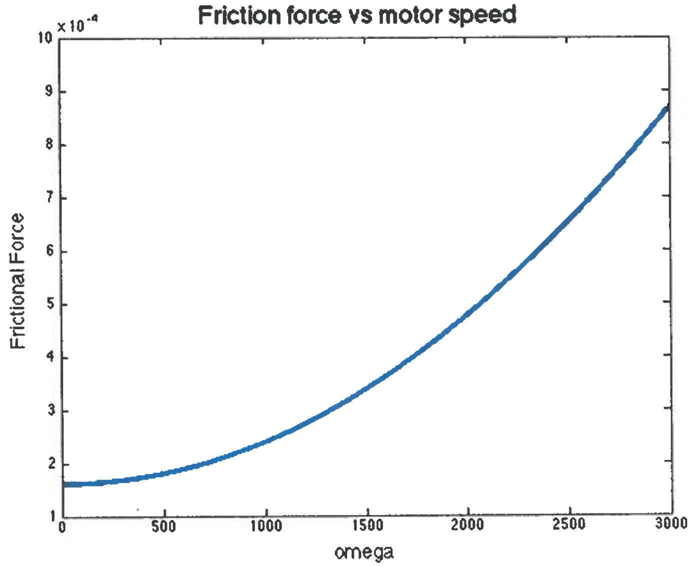
4.1 Motor Performance

To begin our analysis, we characterized the losses and efficiency of our electrical motor. We expected two sources of loss in the motor's conversion of electrical power to mechanical power. First, the motor, like any non-ideal circuit element, has some internal resistance, which steals from the useful mechanical power we can extract from it. This loss goes as the square of current, so we realized that running our motor at an efficient current would be very important. Second, the motor shaft experiences some viscous forces in opposition to its motion, whether from friction inside the motor housing or from the viscous forces on the shaft. The following equations, derived from Kirchoff's law and the Lorentz force model to the motor circuit, allowed us to characterize our motor:

$$V - iR - k\omega = 0 \tag{4.1}$$

$$ki - T_f = T_l \tag{4.2}$$

where V = voltage, i= current, k = the electromagnetic constant, T_f = friction torque, T_l = output load torque, and ω = angular velocity in radians/second. In order to determine the value of our unknown R, k, and T_f, we ran stall and no-load tests on the motor. In the stall test, we drove the motor with a given voltage, and held the motor shaft so that it could not rotate. By setting $\omega = 0$, we were easily able to solve for R by measuring the stall current at given voltages. In the no-load test, we measured the current and rotational velocity of given voltages while the shaft was allowed to rotate freely in order to solve for k. Tabulated data can be found in the Appendix A.1. Knowing these two constants, we used equation 4.2 to generate a polynomial fit curve for frictional T_f as a function of i. For a given voltage, we could use equation 4.1 to transform this curve into a function of ω so that we could make an accurate estimate of the torque force we would experience at our working conditions.



very nice

Figure 4.2: *Having measured R and k, we generated a curve to predict T_f as a function of ω.*

Having characterized our motor constants and frictional force, we were able to generate the following motor curves to determine the power, efficiency, and rotational speed of our motor. We determined that our motor would achieve its peak efficiency (58.6%) if we ran it at 192 mA of current. This became a major design goal, which we came very close to perfectly achieving. In our final test of the crawler on demonstration day, we were able to run at 180 mA, which corresponded to a predicted efficiency of 58.5%. We were proud to have come so close to our goal of maximal motor efficiency.

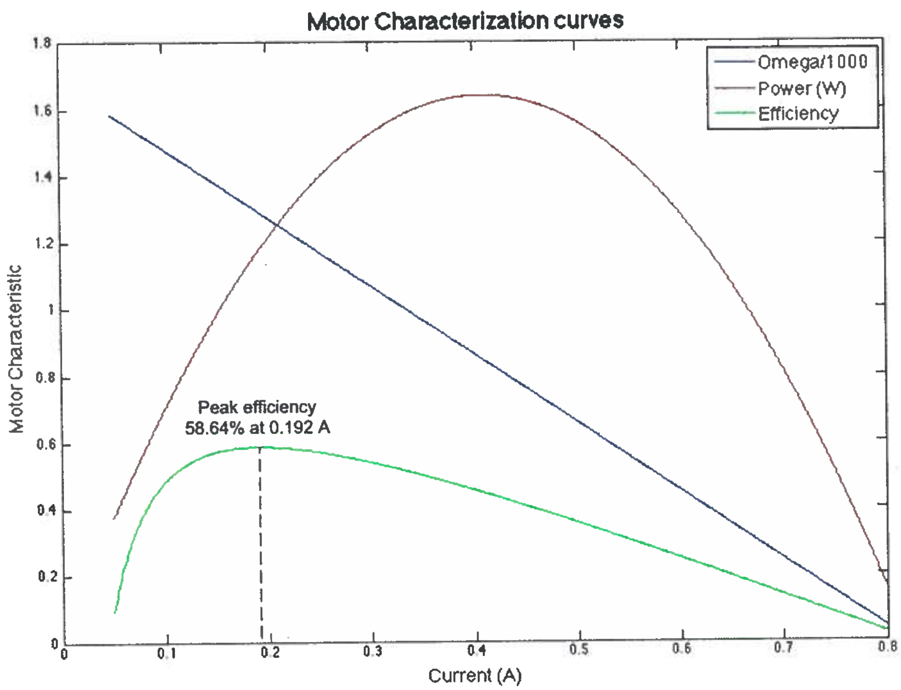


Figure 4.3: *Speed, power and efficiency for our crawler motor as a function of current.*

4.2 Rolling Performance

Our next step in evaluating the efficiency of power-flow through our crawler system involved estimating the rolling resistance in our wheels. We modeled the rolling resistance as a force opposing the direction of motion of the crawler, and alternately as a displaced ground reaction force which introduced a moment opposing the rotation of the wheels. In order to measure this force, we rested our crawler (with transmission disengaged) in its track, balancing its weight with a string over a pulley, attached to another cup of sand. We added weight to the cup until it just began to budge and move uphill. We repeated the procedure, this time removing pinches of sand until the crawler just began to move downhill. We calculated the tension forces at these moments, and halved their difference to estimate the force required to overcome the rolling resistance of the perfectly balanced crawler.

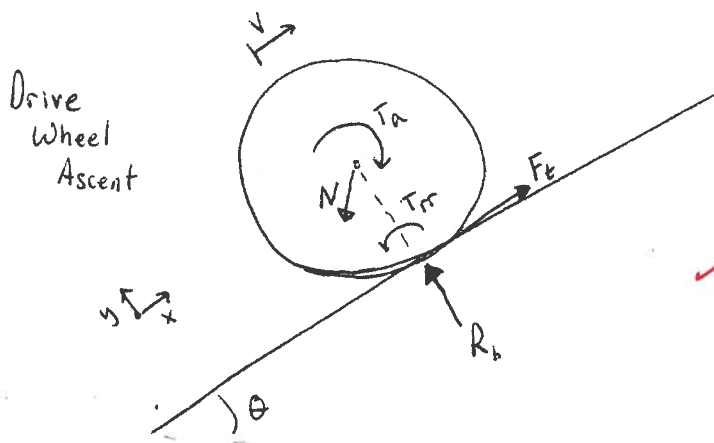


Figure 4.4: *Free Body Diagram of a Drive Wheel, modeling rolling resistance as a torque opposing wheel rotation.*

Since our crawler's weight is highly biased toward its drive wheels, we never experienced any problems with the crawler slipping or losing traction in the lava tube, especially when the crawler is loaded with the egg. As a result, we neglected any losses from slipping of the wheels, and assumed perfect rolling. This made our calculation of rolling efficiency very simple because we assumed the speed of the wheel radius matched the speed of the ground relative to our crawler. Thus, our efficiency simply included force terms:

$$\eta_{roll} = \frac{\sum mg\sin(\theta) - F_{rr}}{\sum mg\sin(\theta)} \tag{4.3}$$

We calculated a rolling efficiency of 91.16% for our crawler fully loaded with the egg, and 94.14% unloaded (see Appendix A.3). This difference demonstrates that our Lego wheels are less efficient at higher normal forces. They are fairly compliant, which explains this result, and indicates that a modification of the wheels to be more rigid would increase the efficiency of our system.

Which is reasonable ✓

4.3 Transmission Performance

Having fully characterized our motor, our wheels, and their associated losses, we faced the challenge of evaluating the performance and efficiency of our transmission gear train. We had decided after some experimentation in the design process that we wanted to make use of the worm gear to reduce speed in few stages, and also because it is not back-driveable. When we built our transmission, and did some preliminary testing of the crawler, we were happy with its energy consumption, because it consistently used close to or less than 12 J. In order to rigorously characterize our motor's efficiency, however, we isolated the system in a "drum test". In this test, we used the crawler to lift a known weight of sand in a cup that was connected to the crawler through a string that wound around one of its drive wheels. Knowing the efficiency of the motor, and measuring the speed and current at which the crawler lifted the known weight, we could back-calculate the efficiency of the transmission. Our first measurements, however, indicated that our transmission operated below 10% efficiency. We were puzzled by this initial result, because it seemed to contradict our testing of the crawler in the lava tube found from the following equation (where we back-calculated an efficiency of 33.44%).

$$E = V * i * t = (\frac{1}{\eta_m})(\frac{1}{\eta_{gt}})(\frac{1}{\eta_{roll}})((m_{crawler} + m_{egg})gl\sin(\theta)) \tag{4.4}$$

indeed.

We decided to redo our drum test, this time emulating the loading of the lava tube as closely as possible. We held our crawler upside-down and at the track's angle in order to mimic the bending moment that would develop in the drive axle as a result of the crawler's weight and the reaction forces of the track on the wheels. We also connected our weight to both wheels so that the load would be evenly split between them, rather than artificially biased to just one side. With these modifications to our testing procedure, we achieved an estimate of our gear train efficiency that was much closer to the efficiency we had back-calculated (29.13%). Data and results are tabulated in the Appendix A.2.

great idea!

OK

4.4 Summary of Performance

In summary, we calculate the total energy losses and use in our crawler system based on the experimental efficiencies of each component of the power flow diagram: Beginning with our demonstration day energy usage of 8.3 J, we estimate a loss of 3.4 J in the motor. We then calculate a loss of 3.2 J in the gear train, and .14 J in the wheels. This left us with 1.5 Joules to raise our 300-gram loaded crawler up 1 meter of a 30-degree incline. Strictly speaking the only useful work done by the crawler was lifting the egg, so a strict estimation of our overall efficiency would be (6.0%). A more generous calculation might include the weight of the crawler, and thus gives us an overall efficiency of (18.1%).

5 Redesign for Egg Mass Changes

The true mass of a protoceratops egg is unknown, and all of our tests have taken place with an approximate mass of 100g. If the mass of the egg is not as expected, there are three possible ways for our crawler to fail:

- 1) The pushing mechanism may fail to provide enough force to push the egg off of the ledge.
- 2) The mass of the egg can cause the crawler to tip and the collector to skid up the track.
- 3) The motor, running at a maximum of nine volts, may provide insufficient torque to push the crawler and egg up the shaft, resulting in motor stall. (or in going so slowly you exceed 5 minutes or 36 J).

5.1 Egg Retrieval Failure

We believe case 1 to be largely a non-issue. The tension on the rubber band, and thus the maximum pushing force of the arm, can be increased to the point where it is nearly rigid and provides equal force to the traction force. This alteration can be made during the operation, as the crawler can always re-ascend the tube to be modified before it has captured the egg.

The arm pushes partly up on the egg, which results in a normal force downwards that increases the traction. Therefore, slippage will not be an issue, and the maximum traction force will be limited by the motor. If the traction force is insufficient to push the egg off of the ledge, then there will clearly not be enough force to drive up the tube with the egg. Thus, this failure mode would fall under case 3.

5.2 Tipping Failure

Case 2 represents the largest concern with our crawler design. Due to the location of the collector, an increased egg weight can cause the crawler to tip. Referencing all of the dimensions from Fig. 5.1, the mass of our crawler ($m_{crawler}$ = .203 kg), and the ratio of rolling resistance force to total weight α_{roll} = .089 (see A.3) we can calculate the maximum weight of the egg before the crawler tips by solving the following system of equations:

$$T_{rr} = \alpha_{roll}(m_{crawler}+m_{egg})gr_{wheel} = .89(.203+m_{egg})(9.8)(.021) = .0372+.1832m_{egg} \quad (5.1)$$

$$\sum F_x = 0 = F_t-(m_{egg}+m_{crawler})g\sin(\theta) = F_t-(.203+m_{egg})(9.8)\sin(30) = F_t-4.9m_{egg}-.9947 \quad (5.2)$$

$$\begin{aligned}\sum M_{@rearaxle} &= 0 = T_{rr} + m_{egg}g(\cos(\theta)e + \sin(\theta)f) + m_{crawler}g(\sin(\theta)c - \cos(\theta)a) + F_t d \\ &= T_{rr} + m_{egg}(9.8)(\cos(30)(.05) + \sin(30)(.04)) + (.203)(9.8)(\sin(30)(.005) - \cos(30)(.0936) + F_t(.021) \\ &= T_{rr} + .62035m_{egg} + .021F_t - .1563\end{aligned} \quad (5.3)$$

The result of this system of linear equations is that $m_{egg} =$ 0.1083 kg. This characteristic is very sensitive to egg weight, and is currently not robust at all. During an actual operation, there would be no way to pull the crawler up to correct for this once the egg landed on the collector. The crawler can likely (we know from witnessing this) go up the incline in the tipped position, skidding on the collector like a pair of runners. However, doing so will lower the efficiency and decrease the maximum allowable weight due to maximum motor torque. In order to rectify this problem, it is prudent to add additional weight to the front of the crawler. An additional 20g of weight centered at the front axle will allow the crawler to stabilize approximately 100g more of egg weight. This weight will slightly reduce efficiency, but the design currently has efficiency to spare. Another possible redesign, one that would fix the problem entirely, is to move the catching mechanism such that it is within the wheel-base.

Oooo. Hmm...

Quite reasonable

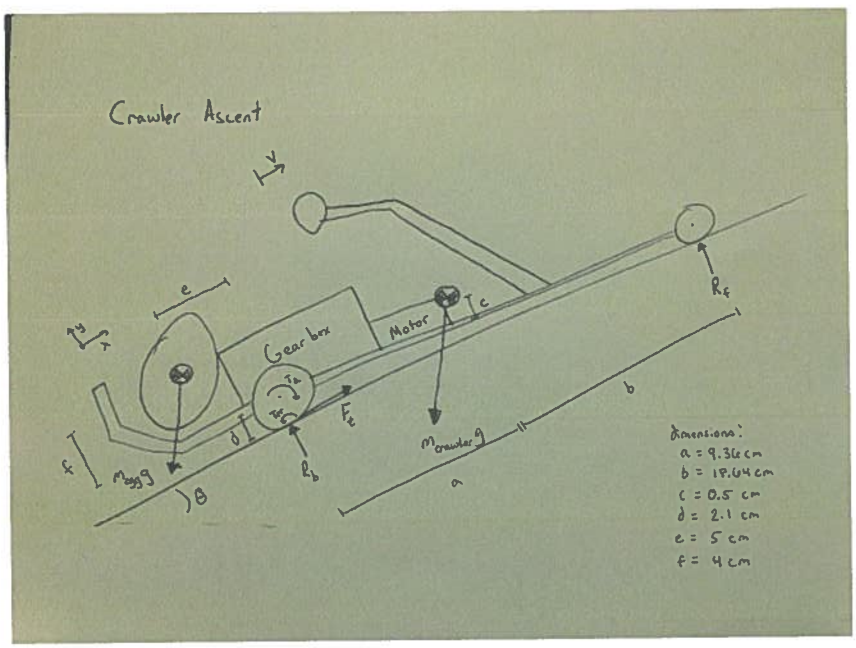


Figure 5.1: *Free body diagram of the crawler ascending the tube. Both the tipping characteristics and the wheel torque are accounted for in this diagram.*

5.3 Insufficient Torque Failure

The third case of failure is related primarily to our gear ratio and gear train efficiency, because it depends the maximum output torque at our wheels. In order to calculate the torque required to overcome gravity and rolling resistance, we used equations 5.2 and 5.1 to equate $F_t + F_{rr}$ as a function of m_{egg} to T_{wheels}/r_{wheels}. In order to find the maximum output torque at the wheels, we rationalized that the power source must output a current nearly equal to the stall current at 9V, the maximum voltage we can use. The friction torque in the motor will be approximately equal to the friction torque (T_f) at $\omega_m = 0$, as the crawler will run very slowly in this case. (Refer to equations A.1, A.2, and A.3 in the appendix.) The resulting equation gives a the maximum output torque (T_a):

$$T_a = (GR)\eta_{gt}(k\frac{V}{R} - T_{f0}) = 180(.2913)(.0047(9/9.755) - .0001598) = .2190Nm \quad (5.4)$$

In order to solve for the maximum mass of the egg that the crawler can theoretically haul up the track, we combine equations to result in the follow:

$$\frac{T_a}{r_{wheels}} = F_t + F_{rr} = 4.9m_{egg} + .9947 + \frac{(.0372 + .1832m_egg)}{r_{wheels}} \quad (5.5)$$

By rearranging and plugging in numbers, we arrive at the solution

$$m_{egg} = \frac{\frac{.2190}{.021} - .9947 - \frac{.0372}{.021}}{4.9 + \frac{.1832}{.021}} = 0.5624 \quad (5.6)$$

Based on this theoretical analysis, our crawler will reach its maximum output torque and be unable to carry an egg over the weight of 562g. This is over five and a half times the expected mass of the egg, making this system very robust to changes in egg weight.

It is possible that the efficiency of our gear train, which we calculated under much lighter loads, will be altered under the heavy load of a 562g egg, or that rolling resistance may increase unexpectedly. Regardless, the force output is sufficient to lift an egg with multiple times the expected mass out of the lava tube while still inputting only 9 volts.

Slippage will not likely affect the crawler's ability to carry an increased egg weight, as the normal force on the drive wheels will increase proportionally with egg weight, and thus the maximum static traction force will increase proportionally by the equation $F_{tmax} = \mu_{static}N$. As the crawler does not currently exhibit slippage, it will not do so under increased egg weight.

OK

6 Conclusions

Our crawler runs smoothly and draws a current very nearly equal to the motor's peak efficiency current, which was our goal. There have no glitches during testing with this final design: our motor runs at near optimal current ranges, and there has been no slipping or unintentional friction as our crawler has been able to stay very straight up the length of the track, often without the assistance of the linear guides. If we were to redesign, we would make a collection basket that would not be unbalanced over the back wheels, because if the egg is twice the expected weight, the crawler will currently tip, which will result in large efficiency losses. However, even with our design, our crawler has still able to make it up the track with the front wheels off on the ascend using only 11 Joules during one test, so such a redesign would be more of prudence than necessity. If this crawler design were to be used in the volcanic tube, it would quickly, silently and safely retrieve the egg (assuming the plastic parts could withstand volcanic temperatures).

A Appendices

A.1 Motor Characterization

A.1.1 Data

Stall Testing

V (V)	i (A)
1.0	.16
2.1	.23
3.0	.34
4.1	.45
4.9	.55
5.9	.65
6.9	.76
8.1	.85
8.9	.95

No Load Testing

V V	i (A)	ω (rad/sec)
1.0	.0347	1765
2.1	.0380	4442
3.1	.0410	6530
4.0	.0440	7850
5.1	.0490	9515
5.9	.0590	11932
7.1	.0730	14017
8.1	.0780	15218
8.9	.0820	16659

A.1.2 Analysis and Results

Equations:

$$V - iR - k\omega_m = 0 \tag{A.1}$$

$$T_L = T_m - T_f \tag{A.2}$$

$$T_m = ki \tag{A.3}$$

$$i_\eta = \sqrt{i_{nl} i_s} \tag{A.4}$$

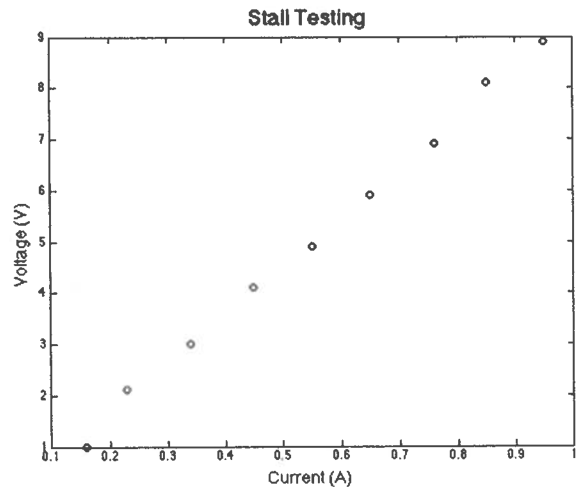


Figure A.1: *A linear fit of our stall test data allowed us to determine R.*

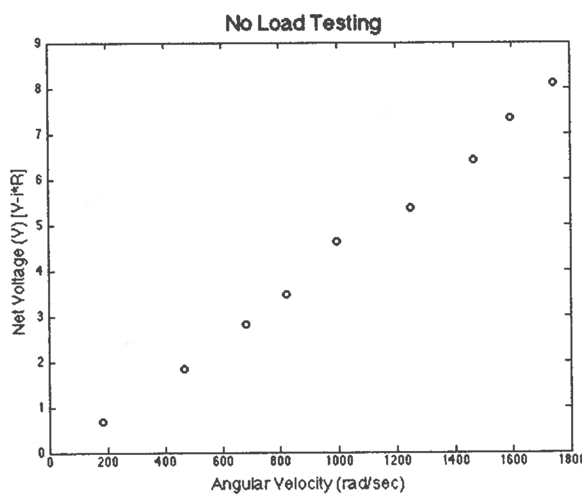


Figure A.2: *A linear fit of our no load data allowed us to determine k.*

$$\eta_m = \frac{P_{out}}{P_{in}} = (\frac{ki - T_f}{Vi})(\frac{V - iR}{k}) \tag{A.5}$$

Results:
$k = .0047$
$R = 9.755\Omega$
$T_f = (.00015976 - .000000567132093\omega_m + .00000007866371\omega_m^2)\text{N}$

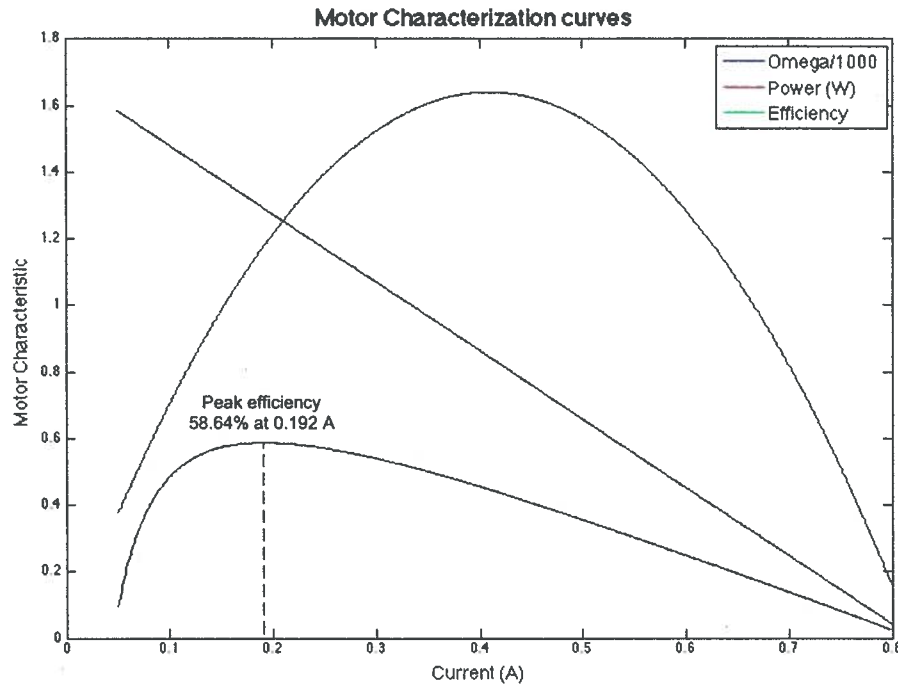


Figure A.3: *Speed, power and efficiency for our crawler motor as a function of current.*

A.2 Gear Train Testing

A.2.1 Data

Gear Train Drum Test, $m = 200g$

V (V)	i (A)	t (s)	d (m)
6.0	.18	4.33	18
7.0	.19	4.09	18
8.0	.19	3.71	18
9.0	.20	3.61	18

A.2.2 Analysis and Results

Equations:

$$T_f = .00015976 - .000000567132093\omega_m + .00000007866371\omega_m^2 \quad (A.6)$$

$$P_{out} = \frac{gmd}{t} \quad (A.7)$$

$$\omega_m = \frac{d(GR)}{r_{wheel}t} \quad (A.8)$$

$$\eta_{gt} = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{(ki - T_f)\omega_m} \tag{A.9}$$

Results

V (V)	ω_m (rad/sec)	T_f (x10^{-3}Nm)	η_{gt} (%)
6.0	1267	.2853	29.20
7.0	1341	.3005	27.64
8.0	1478	.3310	29.13
9.0	1520	.3406	27.32

A.3 Rolling Resistance Testing

Rolling Resistance Pulley Test

	$m_{rolldown}$ (g)	m_{rollup} (g)	F_{rr} (N)	α_{roll}	η_{roll} (%)
w/o egg	75.7	87.6	.05831	.0293	94.14
w/ egg	116	142.7	.13083	.0442	91.16

Equations:

$$F_{rr} = \frac{(m_{rollup} - m_{rolldown})g}{2} \tag{A.10}$$

$$\alpha_{roll} = \frac{F_{rr}}{\sum m} \tag{A.11}$$

$$\eta_{roll} = \frac{(\sum m)\sin(\theta) - \alpha_{roll}(\sum m)}{(\sum m)\sin(\theta)} \tag{A.12}$$

A.4 Variables

Power source and Motor

Variable	Units	Definition
V	Volts	Voltage from power source
i	Amps	Current from power source
i_s	Amps	Motor stall current
i_{nl}	Amps	Motor no load current
i_η	Amps	Current at peak motor efficiency
R	Ohms	Motor internal resistance
k	Volts/second	Motor constant
P	Watts	Power out of the source
P_m	Watts	Power out of the motor
η_m		Motor efficiency
ω_m	Radians/Second	Motor rotational velocity
T_L	Newton*Meter	Motor shaft torque
T_m	Newton*Meter	Theoretical motor output
T_f	Newton*Meter	Motor friction torque

Gear Train and Wheels

Variable	Units	Definition
r_{wheel}	Meter	Radius of drive wheels
T_a	Newton*Meter	Torque acting on rear axle
η_{gt}		Gear train efficiency
T_{rr}	Newton*Meter	Torque of rolling resistance
F_{rr}	Newton	Force of rolling resistance
α_{roll}		Ratio of rolling resistance force to total weight
η_{roll}		Rolling efficiency
GR		Gear ratio
ω_{wheels}	Radians/Second	Wheel rotational velocity

Testing

Variable	**Units**	**Definition**
η		Total crawler efficiency
t	Seconds	Time interval (usually to travel 1 m)
θ	Degress	Tube incline angle
l	Meters	Length of track
h	Meters	Vertical height ascended
$m_{crawler}$	Kilograms	Mass of crawler
m_{egg}	Kilograms	Mass of the egg
m_{weight}	Kilograms	Mass of testing weight
g	Meters/Second^2	Acceleration due to gravity
v	Meters/Second	Velocity