WormMobile:
LEGO Crawler

ME 112 Winter Quarter 2011

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Executive Summary:

For this project, our challenge was to create a robot crawler that would be able to explore steel pipelines of different diameters as well as make ninety degree turns. After multiple iterations, our team finally decided on a final design. Our final crawler, The WormMobile, is a rear-driven machine comprising of a stabilizing gear wheel in the front with two large wheels in the back. The use of a worm gear split into two identical gear transmissions for our large wheels allows for a high torque. However, because of the use of the worm gear, even though our gear ratio was high, our efficiency was not as high as desired. We also found that there was large amount of power loss in the transmission.

During the presentation, our crawler worked smoothly. It climbed up both the vertical shafts and cleared the left and right turns with no difficulty. It ascended 0.9 meters of the shaft in 7.2 seconds at 6.3 Volts and 0.35 Amps. If given more time, our group would have replaced the worm gear in our crawler with another gear train design to increase its efficiency and reduce power loss in the transmission. We also would have used lubricants in our gears.

Background:

Inspired by the 2010 San Bruno gas explosion caused by deteriorating steel pipelines, the goal of this project was to design, manufacture, and analyze a scale model of a robotic crawler that could be used to inspect steel pipelines. The robotic crawler needed to be scaled so that it could descend a 6 inch diameter pipe oriented 20 degrees from horizontal and navigate sharp 90 degree turns. Using the constrains of a Lego kit, electric motor, and readily available office supplies, it needed to meet the mentioned requirements without any use of sensory input. In addition, the crawler was expected to explore the pipe at a speed of roughly 12cm per second.

Basic Description of Design:

The final design of the robotic crawler (Figures 1-6**)** is a rear wheel driven vehicle with two large wheels in the back and one stabilizing wheel in the front. The front wheel is free spinning gear and is expected to slide through the terrain. Using a gear instead of a traditional wheel creates less rolling torque and allows the crawler to make turns without having to overcome as much friction from the sliding front wheel. Previous iterations proved that having a treaded wheel in the front causes the vehicle to run straight into the turn and either flip over or get stuck. The large driving wheels allowed the crawler to easily glide over bumps in the tubing.

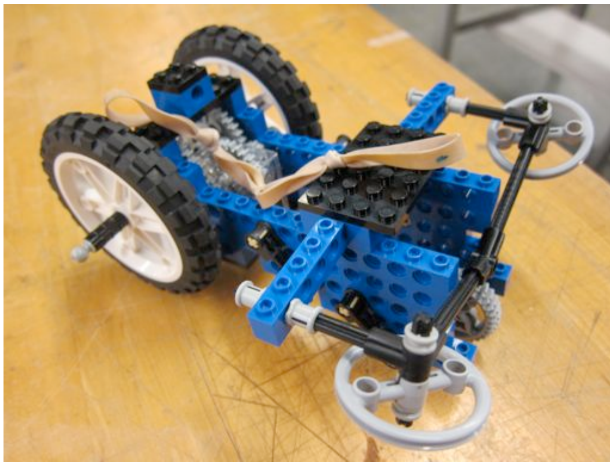


Figure 1: Worm riding WormMobile

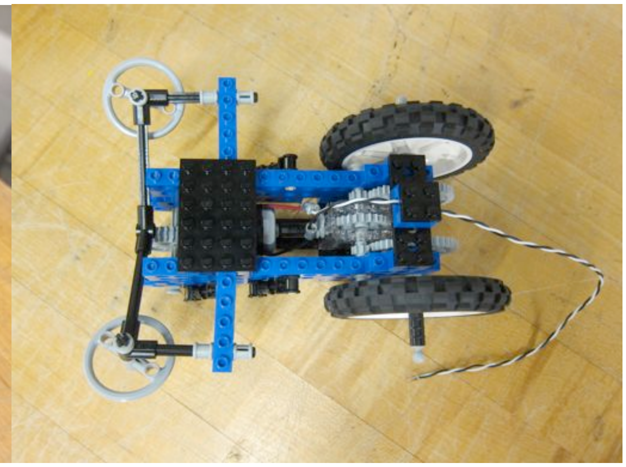


Figure 2: Top View of crawler

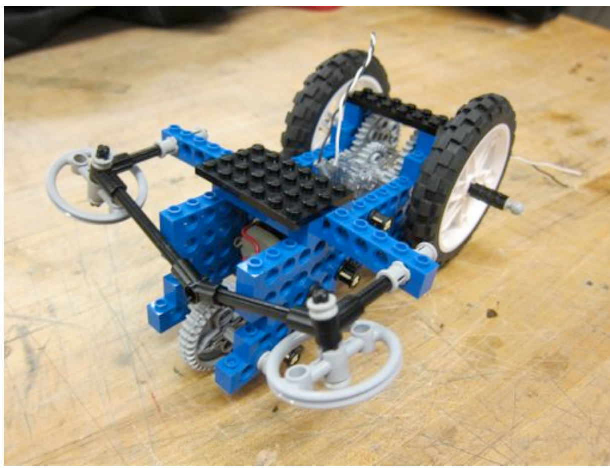


Figure 3: Perspective of crawler

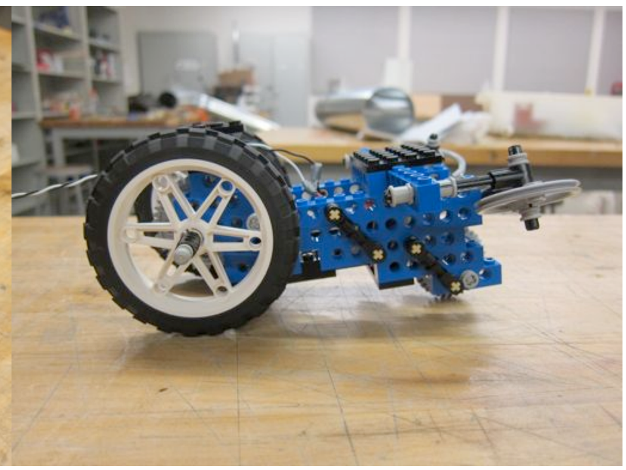


Figure 4: Side view of crawler

Figure 5: Crawler descending pipe

Figure 6: Crawler ascending pipe

The crawler is driven by an electric motor connected to a worm gear and spit into two identical gear transmissions, which are then connected to the wheel axis (as seen in Figure 2**)**. Mirroring the gear transmission distributed the stresses well on the gears. The overall transmission ratio was 120:1 allowing for a higher torque and a reasonable speed. Although we understood the cost in efficiency while using a worm gear, our decision to use it came from being able to resolve the issue of the motor that tended to slip out of contact with the gears. The worm gear also offered a more compact solution to reaching a higher gear ratio.

Additional features of our design included stabilizing bars (Figure 3) that were used on the sides of the crawler. This prevented the disassembly of the individual pieces of the crawler, which would have otherwise occurred due to forces from the motor while running the bot. The protruding front bumper (Figure 5) also helped to allows the crawler to turn with ease with two horizontal wheels in the front aiding in smooth navigation around the corners.

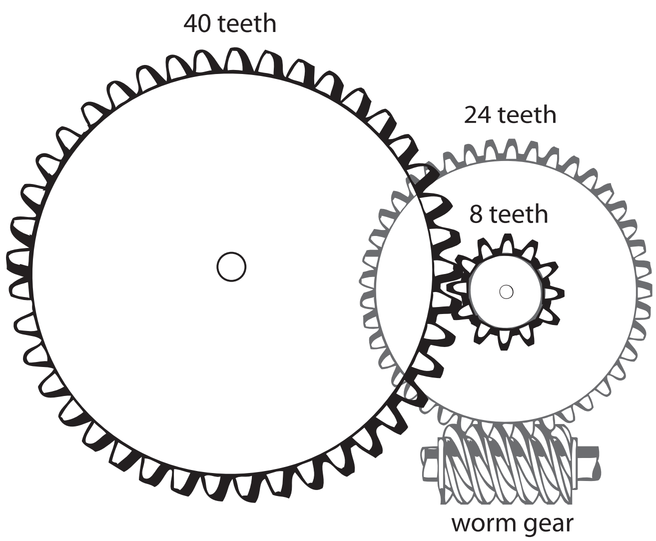


Figure 7: A schematic of the final design transmission

Free Body Diagrams:

After establishing our design for our crawler, we used free body diagrams to look at the different forces that were acting upon our back wheels. In the following free body diagrams, the terms are defined in Appendix A.

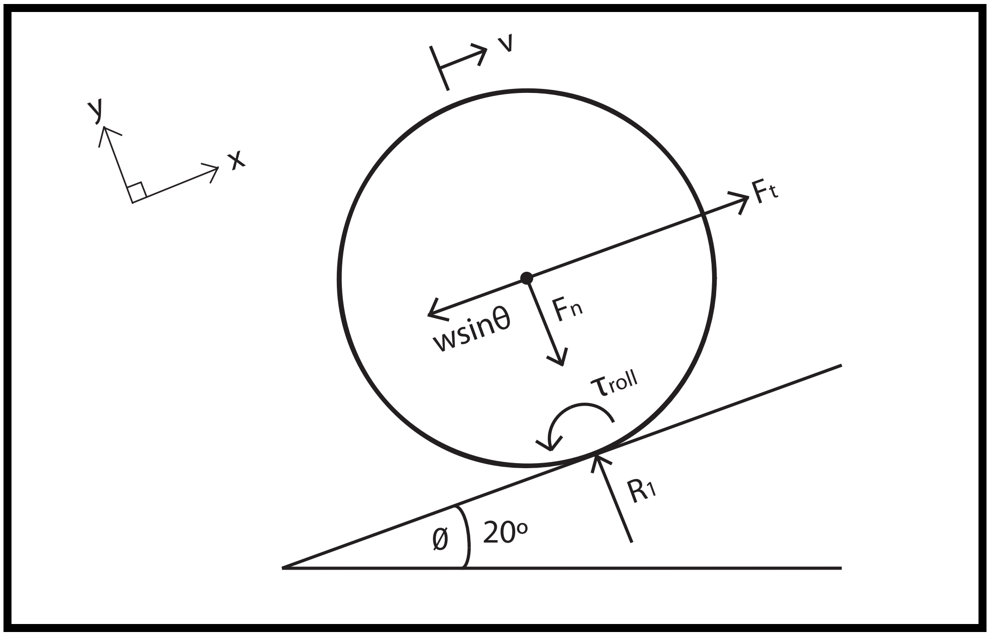


Figure 8: FBD of Back Wheel (Pulley Test)

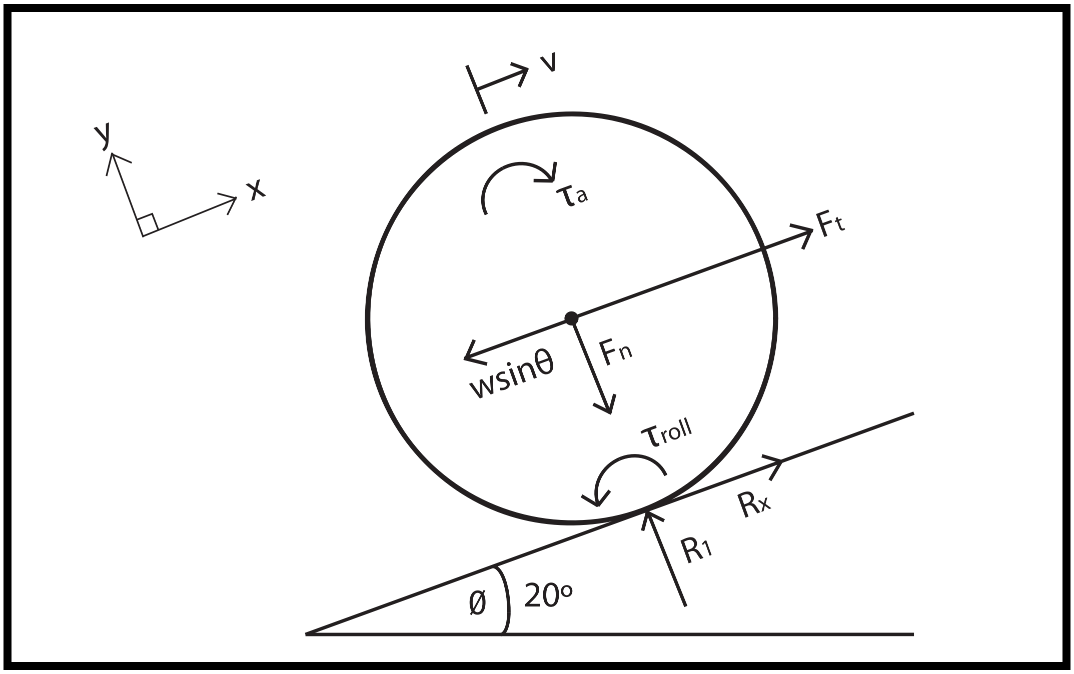


Figure 9: FBD of Back Wheel (Ascending Pipe)

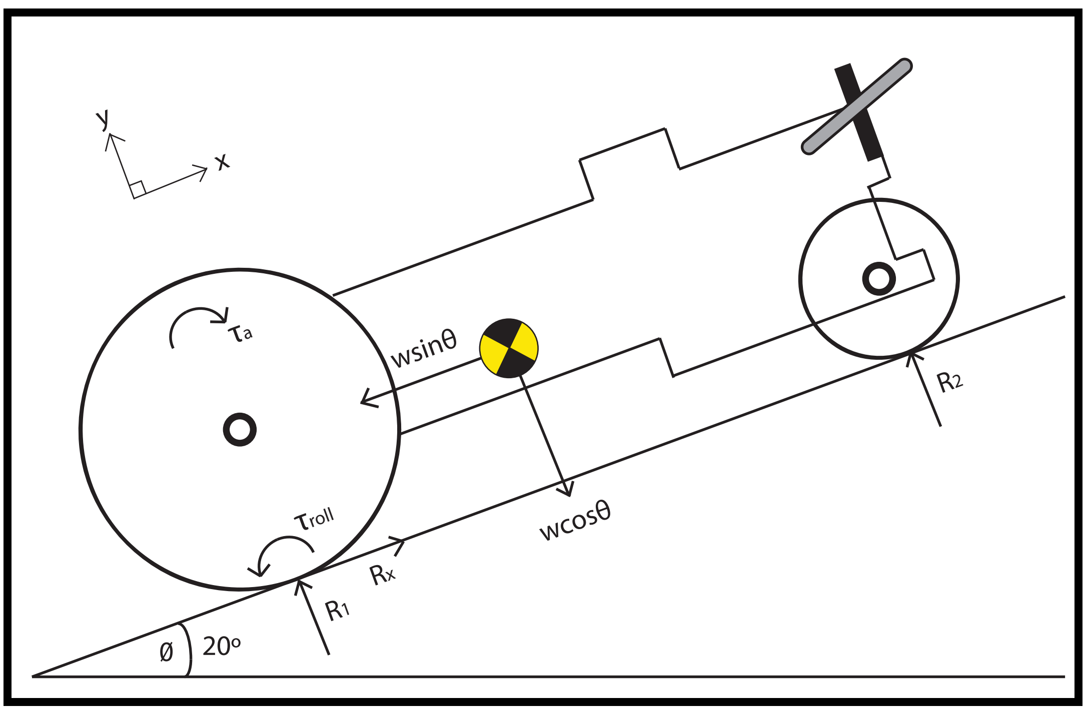


Figure 10: FBD of Entire Crawler (Ascending Pipe)

Analysis of Performance:

Note: Detailed equations and processes on how these values were reached can be found in the attached appendix

For our ascending voltage, we chose to use 6.2V and in the descending case, we used 5V because there was no longer the force of gravity overcome.

Power Losses

Through an analysis of the power transfer, we found that the highest power loss was over the transmission, which is equal to 0.861 W, compared to the motor loss of 0.213W and wheel losses of 0.126W and 0.062W. Calculations of our analysis for power flow (Figure 10) of our crawler can be found in the appendix.

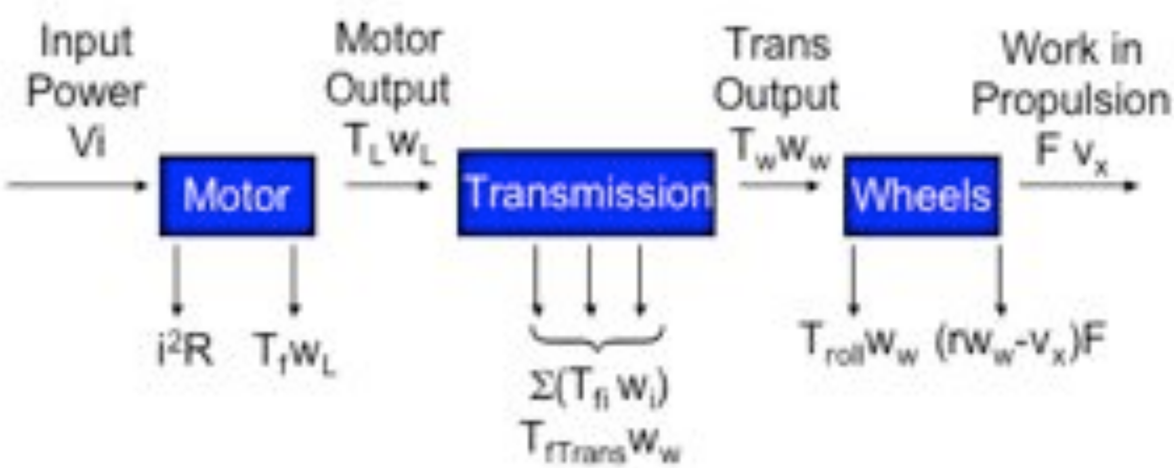


Figure 10 Power Flow Diagram

Overall Efficiencies

We also found that the overall efficiency was low with an overall efficiency of 4.9% while the crawler ascended the tube. The majority of the losses occurred in the transmission and can be attributed to the use of the worm gear. Also, because efficiency scales inversely with weight, our crawler's lightweight design also contributed to the low efficiency of the system.

In terms of power consumption, the WormMobile's final tests all ran less than 2 watts. Ascending, the WormMobile ran at 1.8 Watts and .98 watts descending.

We also graphed our results of power and efficiency versus omega and found that ascending, our max efficiency is 80% and max power is at 1V. The efficiency while descending was found to be 60% with a max power out of 1V. For max power versus efficiency, see figures 11 and 12 for values ascending and descending, respectively.

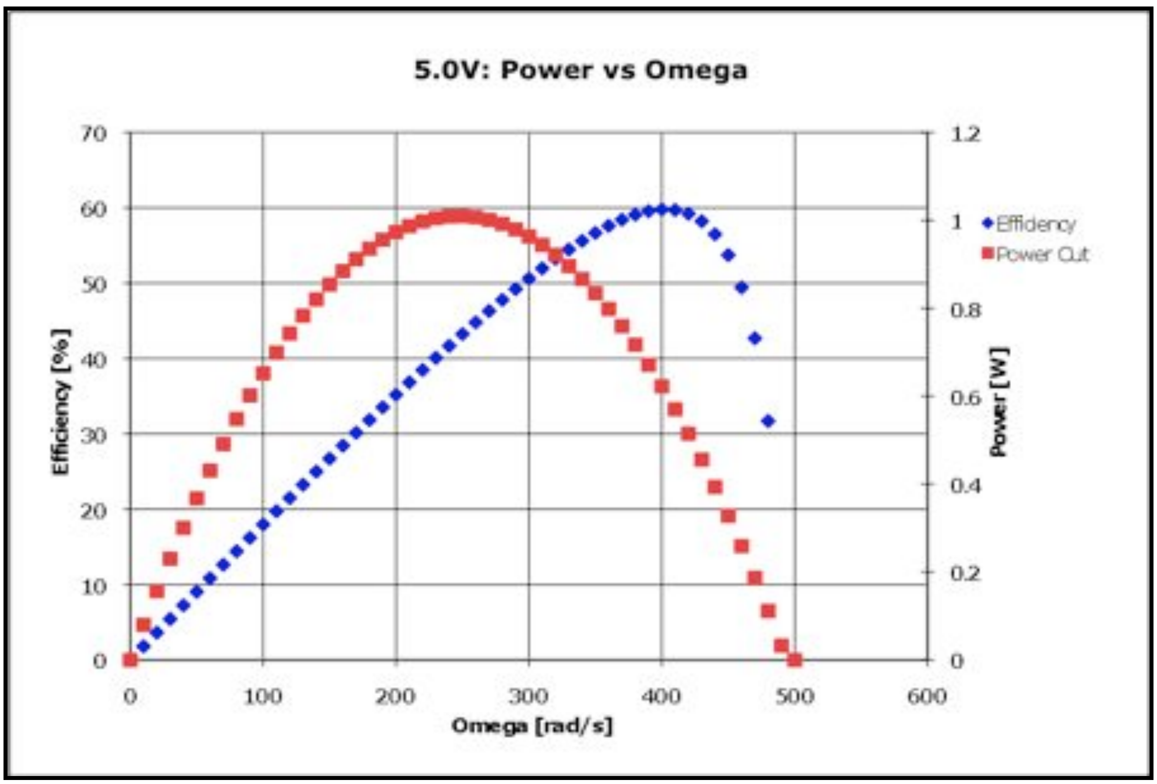


Figure 11: Plot of the motor power & efficiency curve for 5 volts. Data in Appendix D.

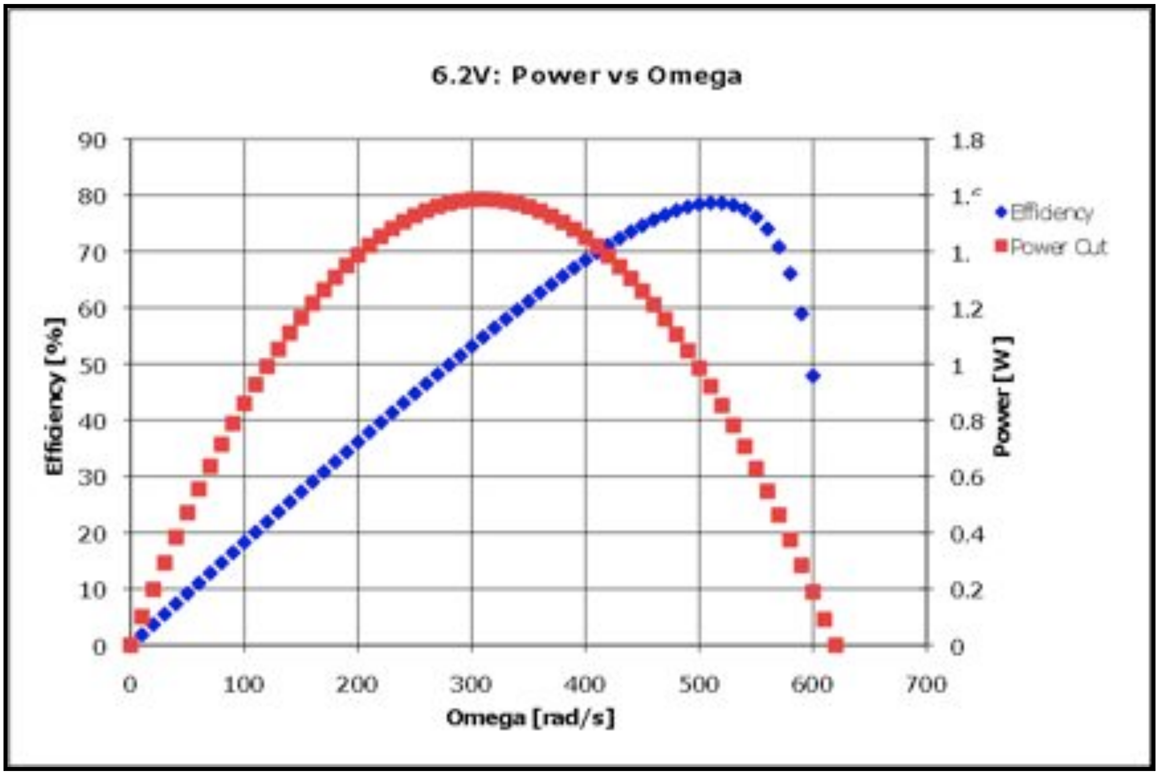


Figure 12: Plot of the motor power & efficiency curve for 6.2 volts. Data in Appendix D.

Analysis of a Gear Train Redesign:

When looking at each element of the power flow system (Figure 10**),** we see that there are 3 stages: the motor, transmission, and wheels. Each element of the system is associated with power losses. From our model of the final crawler system, we see that by far the greatest power loss occurs in the transmission, where .861W is dissipated. This accounts for about 50% of the overall power loss. After examining these results, we realized that the efficiency of our system can be increased by redesigning the transmission. The goal of our gear train redesign is to improve our over all efficiency by operating closer to our peak efficiency of our motor and decrease the losses throughout the system.

The greatest losses in our current gear train was because of the worm gear. The worm gear was great for keeping the gears engaged, though it has a much lower efficiency than typical spur gears. In our redesign, we will only use spur gears.

Our redesign begins with a basic quick estimate of the new gear ratio without considering the losses. To do this we want to pick an input voltage and get the power verse angular velocity graph for the chosen voltage. We decided to stay with the 6.2 V input voltage for the redesign as well. We chose an efficiency lower than the peak efficiency because the curve has a steep drop off right after the motor achieves the max efficiency, thus we chose an efficiency of 75% (instead of the max 78.65%), which means our nominal angular velocity for the motor is 460 radians per second). Now that we have the nominal angular velocity of the motor, we find the angular velocity of the wheel with the following equation :

$$W_{wheel} = V_x / r$$

where

V_x = nominal speed = .12 m/s
r = radius of the wheel = .042 m
ω_{wheel} = angular velocity of the wheel

We get angular velocity of the wheel to be .3 radians per second.

We then can find the gear ratio with the equation

$$GR = \omega_{motor} / \omega_{wheel}$$

This gives us a gear ratio of 161.

A more in-depth analysis is done using Matlab to account for the losses of the system. The calculations can be seen in Appendix E. In these calculations, we use the same nominal values.
From our in-depth analysis, we found the gear ratio we want is 1:152 for a three stage transmission.

Another consideration in our gear redesign is the trade off between the number of gear stages and the amount of stress placed on each gear. With a greater number of gear stages, the overall stress on the gears would be distributed among more gears, resulting in lower stresses on each individual gear. Even though our efficiency would increase with less stages, we decided to have a conservative three stage transmission.

We calculated the overall efficiency power output divided by the power input and found that the overall crawler efficiency for the redesign was 11%. This is a large improvement from the 5% efficiency of the original final design.

Analysis of Gear Stress:

The complete results of our gear stress analysis can be found in the appendix. Our highest calculated stress was about 502psi, which occurred on each of the 8-tooth gears. This makes sense, as the small-tooth gear has the highest torque load with its small radius. Each of the 40-tooth gears and 24-tooth gears had calculated bending stresses of about (45psi) and (86psi), respectively. Because the entire system was split into two identical systems, we were able to spread out the total load between all the gears, and therefore reduce the stress on each gear by a large amount.

We estimated that the ultimate stress of the plastic gears would be around 5000psi. As mentioned before, because we split the gears into two identical systems, the stress on each gear was reduced. Even with the 502psi stress on the 8-tooth gear, this would only contribute to about 10% of the ultimate stress for plastic, so the gears should be ok while the crawler is running at normal conditions.

Also, doing a quick check of load sharing between the gears, we found that the contact ratio of the system was 1.454, which is bigger than one, so that load sharing did occur.

Conclusions:

The final design of our LEGO prototype crawler had a low power consumption of less than 2W for every final trail and accomplished the design goals with ease. The strengths of our project were in functionality, low power consumption, and originality of design. The weakness was in the overall efficiency (of about 5%); however, this could be improved with a the gear train redesign as mentioned above. Our team grappled with the trade off between efficiency and functionality. While the decision to use the worm gear came at the cost of efficiency, we chose to utilize it because it resulted in a smoother operation and a more robust design, especially when connecting to the motor shaft. Given a LEGO motor that we could better mount, removing the worm gear from our design would help our design, as the calculated redesign of the gear train will increase the overall efficiency by about 17%. Overall, our LEGO prototype succeeded in meeting the desired design requirements in terms of power consumption and functionality. The suggested improvements recommend future redesigns that would further increase our transmission efficiency, which was where we saw the most power losses in our current design.

Appendix A: Symbol Definitions for Appendixes B, C, D

Electrical

Symbol	Units	Definition
V	V	Input voltage from power source
I	A	Input current from power source
I_s	A	Motor stall current
R	Ω	Motor Resistance
P_{in}	W	Input power
P_{out}	W	Output power

Mechanical

Symbol	Units	Definition
t	s	Time taken during time trials
d	m	Distance along pipe during time trials
θ	°	Pipe incline angle
ω, ω_L	rad/s and RPM	Motor shaft angular velocity
ω_w	rad/s	Back wheel angular velocity
v_x	m/s	Velocity during time trial
m	kg	Crawler mass
m_{sand}	kg	Mass of sand used to conduct pulley test
$m_{back\ contact}$	kg	Mass measured when the crawler back wheels contacted the scale and the front wheel was supported
$m_{front\ contact}$	kg	Mass measured when the crawler front wheels contacted the scale and the back wheels were supported
g	m/s^2	Gravitational constant
w	N	Crawler weight
$w\sin\theta$	N	Crawler weight force along x axis
F_t	N	Tangential force on back wheels
F_n	N	Normal force on back wheel axel
F_{roll}	N	Rolling friction force on back wheels
F	N	Useful force required to propel crawler forward (does not include F_{roll})
R_1	N	Normal reaction force from ground to back wheels
R_2	N	Normal reaction force from ground to front wheel
R_x	N	Traction force on back wheels
τ_{roll}, T_{roll}	Nm	Rolling friction torque on back wheels
τ_a	Nm	Torque from motor acting on back wheel axel
T_f	Nm	Motor frictional torque
$T_{f,\ trans}$	Nm	Transmission frictional torque
T_L	Nm	Motor shaft torque
T_w	Nm	Back wheel torque

Ratios and Constants

Symbol	Units	Definition
N		Gear ratio
η		Crawler efficiency
K, k	V/s	Motor constant

Appendix B: Force Analysis Calculations

Initial Givens and Calculations

$$\theta = 20°$$

$$r_w = 0.042 \text{ m}$$

$$m = 0.209 \text{ kg}$$

$$m_{\text{back contact}} = 0.127\text{kg}$$

$$m_{\text{front contact}} = 0.082 \text{ kg}$$

$$w = mg = (0.209 \text{ kg})\left(9.81 \frac{\text{m}}{\text{s}^2}\right) = 2.05 \text{ N}$$

$$w \sin\theta = (2.05 \text{ N}) \sin 20° = 0.701 \text{ N}$$

$$R_1 = m_{\text{back contact}} g = (0.127 \text{ kg})\left(9.81 \frac{\text{m}}{\text{s}^2}\right) = 1.25 \text{ N}$$

$$R_2 = m_{\text{front contact}} g = (0.082 \text{ kg})\left(9.81 \frac{\text{m}}{\text{s}^2}\right) = 0.804 \text{ N}$$

Pulley Test

$$m_{\text{sand}} = 0.148 \text{ kg}$$

$$T = m_{\text{sand}} g = (0.148 \text{ kg})\left(9.81 \frac{\text{m}}{\text{s}^2}\right) = 2.05 \text{ N}$$

$$F_t = T = 1.45 \text{ N}$$

$$\sum F_x = F_t - w \sin\theta - F_{\text{roll}} = 0$$

$$\sum F_y = R_1 - F_n = 0$$

$$F_n = R_1 = 1.25 \text{ N}$$

$$F_{\text{roll}} = F_t + w \sin\theta = 1.45 \text{ N} - 0.701 \text{ N} = 0.749 \text{ N}$$

$$\tau_{\text{roll}} = F_{\text{roll}} r_w = (0.749 \text{ N})(0.042 \text{ m}) = 0.0315 \text{ Nm}$$

Driving

$$\sum F_x = R_x - w\sin\theta = 0$$

$$\sum F_y = R_1 - F_n = 0$$

$$\sum M_0 = -\tau_a + \tau_{roll} + R_x r_w = 0$$

$$R_x = w\sin\theta = 0.701\ \text{N}$$

$$\tau_a = \tau_{roll} + R_x r_w = (0.0315\ \text{Nm}) + (0.701\ \text{N})(0.042\ \text{m}) = 0.0609\ \text{Nm}$$

FBD Rear Wheels, Pulley Test Values

Symbol	Magnitude
F_t	1.45 N
$w\sin\theta$	0.701 N
R_1	1.25 N
F_n	1.25 N
τ_{roll}	0.0315 Nm

FBD Rear Wheels, Driving Values

Symbol	Magnitude
R_x	0.701 N
$w\sin\theta$	0.701 N
R_1	1.25 N
F_n	1.25 N
τ_{roll}	0.0315 Nm
τ_a	0.0690 Nm

FBD WormMobile, Driving Values

Symbol	Magnitude
R_x	0.701 N
$w\sin\theta$	0.701 N
R_1	1.25 N
F_n	1.25 N
τ_{roll}	0.0315 Nm
τ_a	0.0690 Nm

Appendix C: Power Analysis Calculations (Left Tube Ascending Test)

Initial Givens and Calculations

$$N = 120$$

$$d = 0.9\ \mathrm{m}$$

$$r_w = 0.042\ \mathrm{m}$$

(From Test Data)

$$V = 6.2\ \mathrm{V}$$

$$I = 0.29\ \mathrm{A}$$

$$t = 7.2\ \mathrm{s}$$

$$v_x = \frac{d}{t} = \frac{0.9\ \mathrm{m}}{7.2\ \mathrm{s}} = 0.125\frac{\mathrm{m}}{\mathrm{s}}$$

(From Motor Power Curve)

$$\omega_L = 480\frac{\mathrm{rad}}{\mathrm{s}}$$

$$T_L = 0.002301\ \mathrm{Nm}$$

(From Force Analysis)

$$w \sin\theta = 0.701\ \mathrm{N}$$

$$F_{roll} = 0.749\ \mathrm{N}$$

$$T_{roll} = 0.0315\ \mathrm{Nm}$$

$$F = w \sin\theta = 0.701\ \mathrm{N}$$

Calculations

1. Power into motor

$$VI = (6.2\ \mathrm{V})(0.29\ \mathrm{A}) = 1.798\ \mathrm{W}$$

2. Power out of motor/into transmission

$$T_L\omega_L = (0.002301\ \text{Nm})\left(480\,\frac{\text{rad}}{\text{s}}\right) = 1.105\ \ \text{W}$$

3. Power out of transmission/into wheels

$$\omega_w = \frac{\omega_L}{N} = \frac{\left(480\,\frac{\text{rad}}{\text{s}}\right)}{120} = 4\,\frac{\text{rad}}{\text{s}}$$

$$T_w = (F_{roll}\ +\ w\sin\theta)\, r_w = (0.749\ \text{N} +\ 0.701\ \text{N})(0.042\ \text{m}) = 0.0609\ \text{Nm}$$

$$T_w\omega_w = (0.0609\ \text{Nm})\left(4\,\frac{\text{rad}}{\text{s}}\right) = 0.244\ \ \text{W}$$

4. Power out of wheels

$$Fv_x = (0.701\ \text{N})\left(0.125\,\frac{\text{m}}{\text{s}}\right) = 0.088\ \ \text{W}$$

5. Power loss due to motor coil resistance

$$I^2R = (0.29\ \text{A})^2(5.569\ \Omega) = 0.468\ \ \text{W}$$

6. Power loss due to motor friction

$$T_f\omega_L = (0.0004433\ \text{Nm})\left(480\,\frac{\text{rad}}{\text{s}}\right) = 0.213\ \ \text{W}$$

7. Power loss from the transmission

$$T_{f,trans}\omega_w =\ T_L\omega_L\ -\ T_w\omega_w\ = 0.861\ \ \text{W}$$

8. Power loss due to wheel rolling friction

$$T_{roll}\omega_w = (0.0315\ \text{Nm})\left(4\,\frac{\text{rad}}{\text{s}}\right) = 0.126\ \ \text{W}$$

9. Power loss due to wheel slippage

$$(r_w\omega_w -\ v_x)F = \left[(0.042\ \text{m})\left(4\,\frac{\text{rad}}{\text{s}}\right) - \left(0.125\,\frac{\text{m}}{\text{s}}\right)\right](0.701\ \text{N}) = 0.088\ \ \text{W}$$

Power Analysis Values

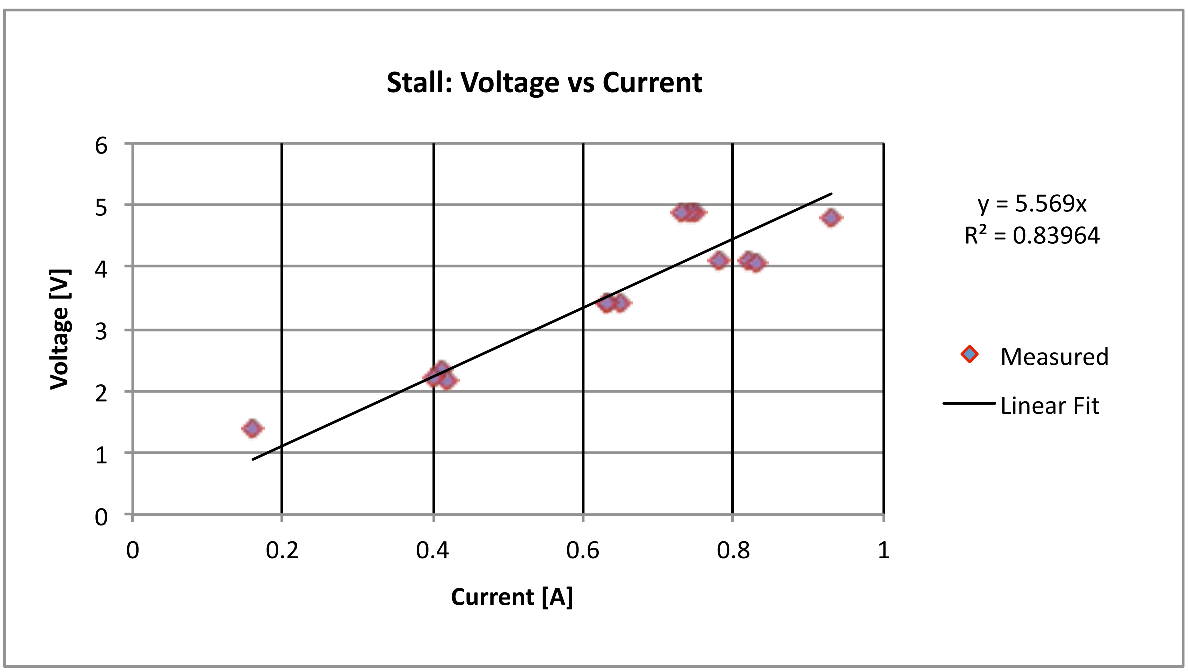
Index	Symbol	Value
1	VI	1.798 W
2	$T_L\omega_L$	1.105 W
3	$T_w\omega_w$	0.244 W
4	Fv_x	0.088 W
5	I^2R	0.468 W
6	$T_f\omega_L$	0.213 W
7	$T_{f,trans}\omega_w$	0.861 W
8	$T_{roll}\omega_w$	0.126 W
9	$(r_w\omega_w - v_x)F$	0.088 W

Appendix D: Motor Power Curves

Stall

$$R = \frac{I}{V}$$

Omega	R [Ohms]	
0	5.569	
	Stall	
I [A]	V [V]	R [Ohms]
0.16	1.39	0.115107914
0.41	2.35	0.174468085
0.42	2.162	0.19426457
0.4	2.189	0.182731841
0.63	3.42	0.184210526
0.65	3.39	0.191740413
0.63	3.42	0.184210526
0.82	4.08	0.200980392
0.78	4.11	0.189781022
0.83	4.05	0.204938272
0.93	4.79	0.194154489
0.75	4.87	0.154004107
0.74	4.87	0.151950719
0.73	4.87	0.149897331

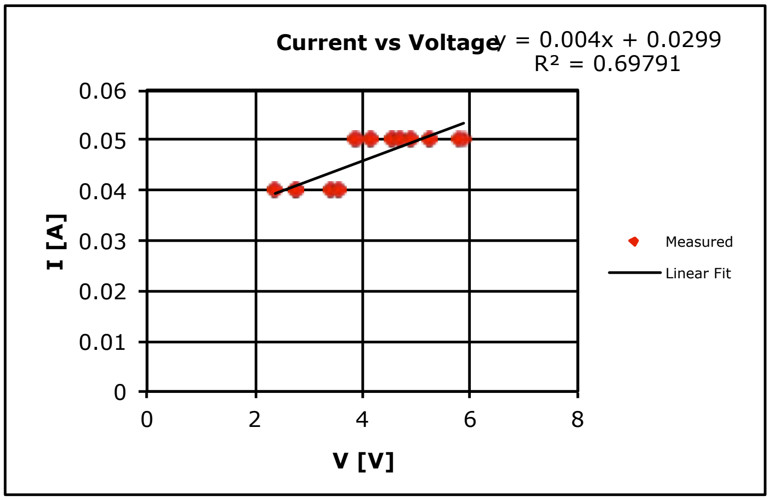


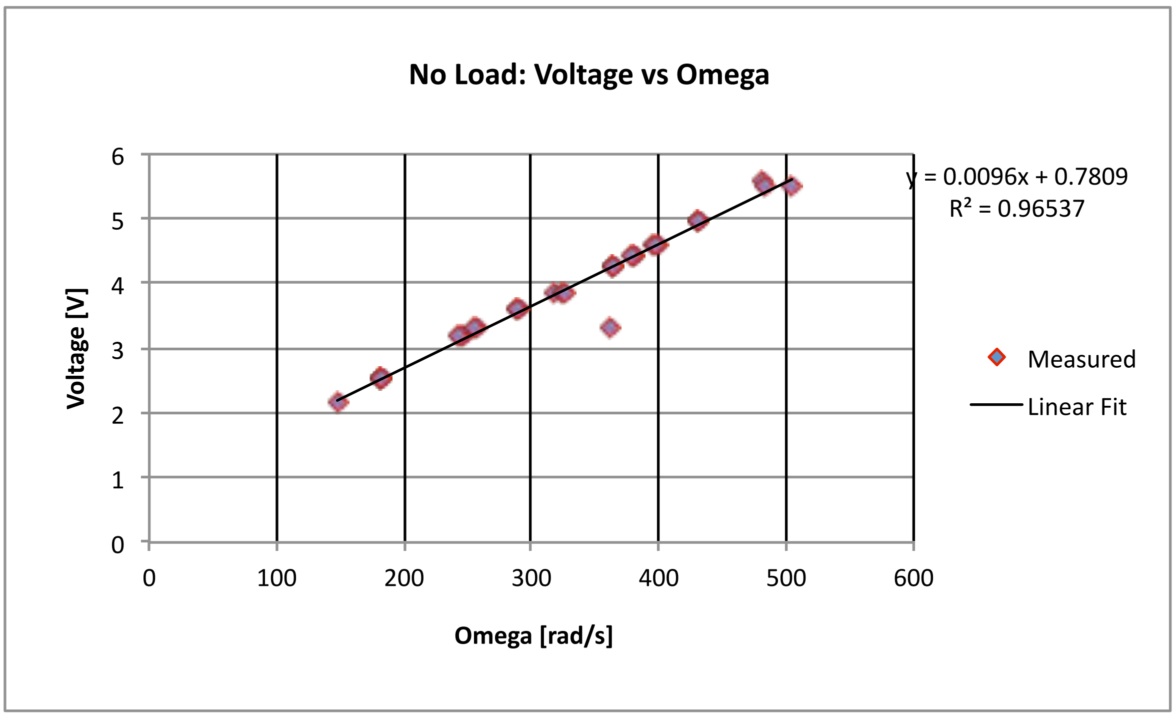
No Load

$$T_f = K * ave(I)$$

$$I_s = \frac{V}{R}$$

R[Ohms]	RPM to rad/s	K[V/s]	T_f[Nm]	
5.569	0.104719755	0.0096	0.000443294	
No Load				
V-IR	**Omega [RPM]**	**Omega [rad/s]**	**V [V]**	**I [A]**
2.15824	14.26	1.493303708	2.381	0.04
2.15824	14.17	1.48387893	2.381	0.04
2.15824	1409	147.550135	2.381	0.04
2.52824	1743	182.5265332	2.751	0.04
2.52324	1743	182.5265332	2.746	0.04
2.52124	1745	182.7359727	2.744	0.04
2.52024	1738	182.0029344	2.743	0.04
3.17724	2365	247.6622209	3.4	0.04
3.17724	2334	244.4159084	3.4	0.04
3.17724	2316	242.5309529	3.4	0.04
3.33724	3459	362.225633	3.56	0.04
3.33724	2454	256.9822791	3.56	0.04
3.32724	2428	254.2595654	3.55	0.04
3.61155	2764	289.4454032	3.89	0.05
3.60155	2768	289.8642822	3.88	0.05
3.59155	2761	289.1312439	3.87	0.05
3.87155	3033	317.6150173	4.15	0.05
3.87155	3100	324.6312409	4.15	0.05
3.87155	3122	326.9350755	4.15	0.05
4.25155	3469	363.2728305	4.53	0.05
4.25155	3473	363.6917095	4.53	0.05
4.25155	3484	364.8436268	4.53	0.05
4.42155	3642	381.3893481	4.7	0.05
4.42155	3637	380.8657494	4.7	0.05
4.42155	3623	379.3996728	4.7	0.05
4.61155	3813	399.2964263	4.89	0.05
4.61155	3784	396.2595534	4.89	0.05
4.60155	3796	397.5161904	4.88	0.05
4.97155	4121	431.5501108	5.25	0.05
4.96155	4119	431.3406713	5.24	0.05
4.96155	4119	431.3406713	5.24	0.05
5.60155	4588	480.4542365	5.88	0.05
5.52155	4609	482.6533513	5.8	0.05
5.52155	4816	504.3303407	5.8	0.05


Current vs Voltage
y = 0.004x + 0.0299
R² = 0.69791
0.06
0.05
0.04
0.03
0.02
0.01
0
I [A]
0
2
4
6
8
V [V]
Measured
Linear Fit


No Load: Voltage vs Omega
y = 0.0096x + 0.7809
R² = 0.96537
6
5
4
3
2
1
0
Voltage [V]
0
100
200
300
400
500
600
Omega [rad/s]
Measured
Linear Fit

Power Curves

$$\mathbf{I} = \frac{\mathbf{V} - \mathbf{K}\boldsymbol{\omega}}{\mathbf{R}}$$

$$\mathbf{P_{in}} = \mathbf{VI}$$

$$\mathbf{P_{out}} = \mathbf{T_L}\omega$$

$$\boldsymbol{\eta} = \mathbf{KI} - \mathbf{T_f}$$

At 5 Volts

V [V]	**R [Ohms]**	**RPM to rad/s**	**K [V/s]**	**T_f [Nm]**	**I_s [A]**	
5	5.569	0.104719755	0.0096	0.000443294	0.897827258	
I [A]	**Omega [rad/s]**	**Omega [RPM]**	**T_L [Nm]**	**P_in [W]**	**P_out [W]**	**Efficiency [%]**
0.897827258	0	0	0.008175848	4.48913629	0	0
0.880588975	10	95.49296586	0.00801036	4.402944873	0.0801036	1.819318722
0.863350691	20	190.9859317	0.007844873	4.316753457	0.15689745	3.634616893
0.846112408	30	286.4788976	0.007679385	4.23056204	0.23038155	5.445648777
0.828874125	40	381.9718634	0.007513897	4.144370623	0.300555899	7.25214819
0.811635841	50	477.4648293	0.00734841	4.058179206	0.367420498	9.05382634
0.794397558	60	572.9577951	0.007182922	3.97198779	0.430975346	10.85036936
0.777159275	70	668.450761	0.007017435	3.885796373	0.491220444	12.64143556
0.759920991	80	763.9437268	0.006851947	3.799604956	0.548155792	14.4266522
0.742682708	90	859.4366927	0.00668646	3.713413539	0.601781389	16.20561197
0.725444424	100	954.9296586	0.006520972	3.627222122	0.652097236	17.97786884
0.708206141	110	1050.422624	0.006355485	3.541030706	0.699103332	19.74293335
0.690967858	120	1145.91559	0.006189997	3.454839289	0.742799678	21.50026719
0.673729574	130	1241.408556	0.00602451	3.368647872	0.783186274	23.24927696
0.656491291	140	1336.901522	0.005859022	3.282456455	0.820263119	24.98930694
0.639253008	150	1432.394488	0.005693535	3.196265039	0.854030213	26.71963067
0.622014724	160	1527.887454	0.005528047	3.110073622	0.884487558	28.43944116
0.604776441	170	1623.38042	0.00536256	3.023882205	0.911635152	30.14783943
0.587538158	180	1718.873385	0.005197072	2.937690788	0.935472995	31.84382097
0.570299874	190	1814.366351	0.005031585	2.851499372	0.956001088	33.52625983
0.553061591	200	1909.859317	0.004866097	2.765307955	0.973219431	35.19388969
0.535823308	210	2005.352283	0.00470061	2.679116538	0.987128023	36.84528125
0.518585024	220	2100.845249	0.004535122	2.592925121	0.997726865	38.47881519
0.501346741	230	2196.338215	0.004369635	2.506733704	1.005015957	40.09264945
0.484108458	240	2291.831181	0.004204147	2.420542288	1.008995298	41.68467963
0.466870174	250	2387.324146	0.00403866	2.334350871	1.009664889	43.2524905
0.449631891	260	2482.817112	0.003873172	2.248159454	1.007024729	44.79329645
0.432393607	270	2578.310078	0.003707685	2.161968037	1.001074819	46.30386766
0.415155324	280	2673.803044	0.003542197	2.075776621	0.991815158	47.78043786
0.397917041	290	2769.29601	0.003376709	1.989585204	0.979245747	49.21858815
0.380678757	300	2864.788976	0.003211222	1.903393787	0.963366586	50.61309922
0.363440474	310	2960.281942	0.003045734	1.81720237	0.944177674	51.95776154
0.346202191	320	3055.774907	0.002880247	1.731010953	0.921679012	53.24512883
0.328963907	330	3151.267873	0.002714759	1.644819537	0.8958706	54.46619399
0.311725624	340	3246.760839	0.002549272	1.55862812	0.866752437	55.6099576

0.294487341	350	3342.253805	0.002383784	1.472436703	0.834324523	56.66284476
0.277249057	360	3437.746771	0.002218297	1.386245286	0.79858686	57.60790442
0.260010774	370	3533.239737	0.002052809	1.30005387	0.759539445	58.42369022
0.242772491	380	3628.732702	0.001887322	1.213862453	0.717182281	59.08266453
0.225534207	390	3724.225668	0.001721834	1.127671036	0.671515366	59.54887059
0.208295924	400	3819.718634	0.001556347	1.041479619	0.622538701	59.77444868
0.191057641	410	3915.2116	0.001390859	0.955288203	0.570252285	59.69426643
0.173819357	420	4010.704566	0.001225372	0.869096786	0.514656119	59.21735382
0.156581074	430	4106.197532	0.001059884	0.782905369	0.455750202	58.21268063
0.13934279	440	4201.690498	0.000894397	0.696713952	0.393534535	56.48437696
0.122104507	450	4297.183463	0.000728909	0.610522535	0.328009118	53.72596401
0.104866224	460	4392.676429	0.000563422	0.524331119	0.25917395	49.42944271
0.08762794	470	4488.169395	0.000397934	0.438139702	0.187029032	42.68707695
0.070389657	480	4583.662361	0.000232447	0.351948285	0.111574363	31.70191981
0.053151374	490	4679.155327	6.69591E-05	0.265756868	0.032809944	12.34584992
0.03591309	500	4774.648293	0	0.179565452	0	0

At 6.2 Volts

V [V]	**R [Ohms]**	**RPM to rad/s**	**K [V/s]**	**T_f [Nm]**	**I_s [A]**	
6.2	5.569	0.104719755	0.0096	0.000443294	1.1133058	
I [A]	**Omega [rad/s]**	**Omega [RPM]**	**T_L [Nm]**	**P_in [W]**	**P_out [W]**	**Efficiency [%]**
1.1133058	0	0	0.010244442	5.566529	0	0
1.096067517	10	95.49296586	0.010078954	5.480337583	0.10078954	1.839111896
1.078829233	20	190.9859317	0.009913467	5.394146166	0.19826933	3.675638819
1.06159095	30	286.4788976	0.009747979	5.30795475	0.29243937	5.509454844
1.044352667	40	381.9718634	0.009582491	5.221763333	0.383299659	7.34042573
1.027114383	50	477.4648293	0.009417004	5.135571916	0.470850198	9.168408227
1.0098761	60	572.9577951	0.009251516	5.049380499	0.555090986	10.9932493
0.992637816	70	668.450761	0.009086029	4.963189082	0.636022024	12.81478529
0.975399533	80	763.9437268	0.008920541	4.876997666	0.713643312	14.63284096
0.95816125	90	859.4366927	0.008755054	4.790806249	0.787954849	16.44722847
0.940922966	100	954.9296586	0.008589566	4.704614832	0.858956636	18.25774621
0.923684683	110	1050.422624	0.008424079	4.618423415	0.926648672	20.06417751
0.9064464	120	1145.91559	0.008258591	4.532231999	0.991030958	21.86628925
0.889208116	130	1241.408556	0.008093104	4.446040582	1.052103494	23.6638302
0.871969833	140	1336.901522	0.007927616	4.359849165	1.109866279	25.45652928
0.85473155	150	1432.394488	0.007762129	4.273657748	1.164319314	27.24409352
0.837493266	160	1527.887454	0.007596641	4.187466331	1.215462598	29.02620587
0.820254983	170	1623.38042	0.007431154	4.101274915	1.263296132	30.80252259
0.8030167	180	1718.873385	0.007265666	4.015083498	1.307819916	32.57267044
0.785778416	190	1814.366351	0.007100179	3.928892081	1.349033949	34.33624342
0.768540133	200	1909.859317	0.006934691	3.842700664	1.386938232	36.09279912
0.75130185	210	2005.352283	0.006769204	3.756509248	1.421532764	37.8418545
0.734063566	220	2100.845249	0.006603716	3.670317831	1.452817546	39.58288118
0.716825283	230	2196.338215	0.006438229	3.584126414	1.480792577	41.31529992
0.699586999	240	2291.831181	0.006272741	3.497934997	1.505457859	43.03847441
0.682348716	250	2387.324146	0.006107254	3.411743581	1.526813389	44.75170402
0.665110433	260	2482.817112	0.005941766	3.325552164	1.54485917	46.45421553
0.647872149	270	2578.310078	0.005776279	3.239360747	1.559595199	48.14515336
0.630633866	280	2673.803044	0.005610791	3.15316933	1.571021479	49.82356843
0.613395583	290	2769.29601	0.005445303	3.066977913	1.579138008	51.48840496

0.596157299	300	2864.788976	0.005279816	2.980786497	1.583944787	53.13848505
0.578919016	310	2960.281942	0.005114328	2.89459508	1.585441815	54.7724905
0.561680733	320	3055.774907	0.004948841	2.808403663	1.583629093	56.3889413
0.544442449	330	3151.267873	0.004783353	2.722212246	1.57850662	57.98616998
0.527204166	340	3246.760839	0.004617866	2.63602083	1.570074398	59.56229101
0.509965883	350	3342.253805	0.004452378	2.549829413	1.558332424	61.11516388
0.492727599	360	3437.746771	0.004286891	2.463637996	1.543280701	62.64234855
0.475489316	370	3533.239737	0.004121403	2.377446579	1.524919226	64.14105115
0.458251033	380	3628.732702	0.003955916	2.291255163	1.503248002	65.60805739
0.441012749	390	3724.225668	0.003790428	2.205063746	1.478267027	67.03965043
0.423774466	400	3819.718634	0.003624941	2.118872329	1.449976302	68.43150867
0.406536182	410	3915.2116	0.003459453	2.032680912	1.418375826	69.77857751
0.389297899	420	4010.704566	0.003293966	1.946489495	1.3834656	71.07490705
0.372059616	430	4106.197532	0.003128478	1.860298079	1.345245623	72.31344474
0.354821332	440	4201.690498	0.002962991	1.774106662	1.303715896	73.48576747
0.337583049	450	4297.183463	0.002797503	1.687915245	1.258876419	74.58173166
0.320344766	460	4392.676429	0.002632016	1.601723828	1.210727191	75.58901039
0.303106482	470	4488.169395	0.002466528	1.515532412	1.159268213	76.49247248
0.285868199	480	4583.662361	0.002301041	1.429340995	1.104499484	77.27333704
0.268629916	490	4679.155327	0.002135553	1.343149578	1.046421005	77.90800239
0.251391632	500	4774.648293	0.001970066	1.256958161	0.985032776	78.36639328
0.234153349	510	4870.141259	0.001804578	1.170766744	0.920334796	78.60957791
0.216915066	520	4965.634224	0.001639091	1.084575328	0.852327066	78.58624885
0.199676782	530	5061.12719	0.001473603	0.998383911	0.781009585	78.22738096
0.182438499	540	5156.620156	0.001308115	0.912192494	0.706382354	77.43786086
0.165200215	550	5252.113122	0.001142628	0.826001077	0.628445373	76.0828757
0.147961932	560	5347.606088	0.00097714	0.739809661	0.547198641	73.96478721
0.130723649	570	5443.099054	0.000811653	0.653618244	0.462642159	70.78170834
0.113485365	580	5538.59202	0.000646165	0.567426827	0.374775926	66.04832703
0.096247082	590	5634.084985	0.000480678	0.48123541	0.283599943	58.93164495
0.079008799	600	5729.577951	0.00031519	0.395043994	0.18911421	47.87168342
0.061770515	610	5825.070917	0.000149703	0.308852577	0.091318726	29.5670922
0.044532232	620	5920.563883	0	0.22266116	0	0

Appendix E: Gear Train Redesign Analysis

Note: To find the losses in of the transmission, we will use an efficiency loss of 35%, which is a reasonable value for each stage of spur gears. So if we take it to be 65% efficient at each stage, then (.65^3) = 0.421875, which is a total transmission efficiency of 42.19% transmission.

```
% Redesign.m

clear all; close all; clc;
%----------------------------------------------------------------------

% Constants
g = 9.81; % Gravitational constant[m/s^2]
m = 0.209; % Crawler mass [kg]
theta = 20; % Pipe incline angle [deg]
T_roll = 0.0315; % Back wheels rolling torque[Nm]
r_w = 0.042; % Back wheel radius [m]
R = 5.569; % Motor resistance [Ohms]
K = 0.0096; % Motor constant [V/s]
T_f = 0.000443; % Motor frictional torque[Nm]

% Inputs
V_in = 6.2; % Input voltage from power source[V]
Eff = 0.76; % Efficiency estimate taken from our Power vs. Omega graph
omega_l =  460; % Motor shaft angular velocity estimate taken from the wanted
efficiency on our Power vs. Omega graph [rad/s]
E_stage = 0.65; % Estimate of efficiency per stage of gearing
n_stages = 3; % Number of stages in gearing
%----------------------------------------------------------------------

% Commands

% Start at the beginning of the power transfer display
I = (V_in - K*omega_l)/R; % Input current from power source[A]
P_in = V_in*I;  % Input power [W]
Loss_m1 = I^2*R; % Power resistive loss over motor [W]
Loss_m2 = T_f*omega_l; % Power frictional loss over motor [W]

Motor_out = P_in - Loss_m1 - Loss_m2; % Power out of motor [W]
T_l = Motor_out/omega_l; % Motor output torque [Nm]

Trans_out= E_stage^n_stages*Motor_out; % Transmission output torque [Nm]

% Now we must start at the back before we can obtain omega_w
Vx = .12; % Crawler velocity along x axis[m/s]
F = m*g*sin(theta); % Useful force required to propel crawler [N]
T_w = T_roll + r_w*F; % Back wheels torque [Nm]

omega_w = Trans_out/T_w % Back wheel angular velocity [rad/s]
N = omega_l/omega_w % Gives us an approximate total gear ratio
Eff_trans = E_stage^n_stages % Transmission efficiency
P_out = F*Vx % Wheel output power [W]
Eff_total = P_out/P_in % Total crawler efficiency

fprintf('For comparison, our original design had omega_w = 4 rad/s, N = 120,
and Eff_total = 0.22')
```

Command Window Output:

```
omega_w =

    3.0199


N =

  152.3254


Eff_trans =

    0.2746


P_out =

    0.2246


Eff_total =

    0.1131
```

For comparison, our original design had omega_w = 4 rad/s, N = 120, and Eff_total = 0.22>>

Appendix F: Gear Stress Analysis

useful conversion factors	
m_to_inch	39.37
N_to_lbf	0.2248
Nm_to_inlbf	8.850376
in/s_to_ft/min	5
in/s_to_mph	0.056818182

PitchDia	# of teeth / Pitch
Ftan	Tmotor / (0.5 * PitchDia)
Vtan	Omega_motor * (PitchDia / 2)
Kv	((A_AGMA+SQRT(Vtan))/A_AGMA)^B_AGMA
Sigma_L	(Ftan*Pitch/(b_width*Jlewis))*K_o*K_m*Kv

Inputs (roughly similar to 09 crawler)		
Tmotor	4.43E-02	inch lbf
	5.00E-03	Nm
Omega_motor	4.58E+03	rpm
	4.80E+02	rad/sec
Input power	1.78E+00	Watts
	2.39E-03	horsepower

Gear types		
Pitch	27.3	diametral pitch (teeth/inch)
b_width	0.25	face width (inches)
K_o	1.5	(1.5 for mod. Shock) 15.1
K_m	1.6	(1.3 for b<=2 and precise) 15.2
Q_v	8	AGMA quality
phi	0.34906585	radians

B_AGMA	0.629960525
A_AGMA	70.7222106

		PitchDia (inch)	Ftan (lbf)	Vtan (in/s)	Vtan (ft/min)	Kv (AGMA)	Jlewis (15.23)	Sigma_L (psi)
N1_driver	24	0.879120879	0.10	210.99	1054.94	1.27	0.39	85.84
N1_driven	8	0.293040293	0.30	210.99	1054.94	1.27	0.20	502.15
N2_driver	8	0.293040293	0.30	210.99	1054.94	1.27	0.20	502.15
N2_driven	40	1.465201465	0.06	210.99	1054.94	1.27	0.45	44.64

T_2	1.48E-02	inch lbf
T_3	7.38E-02	inch lbf
omega_2	1.44E+03	rad/s
omega_3	2.88E+02	rad/s

S_ult	5000	psi
Sn_prime	2500	for infinite life
Sn_adj	2088.45	psi adjust life stress

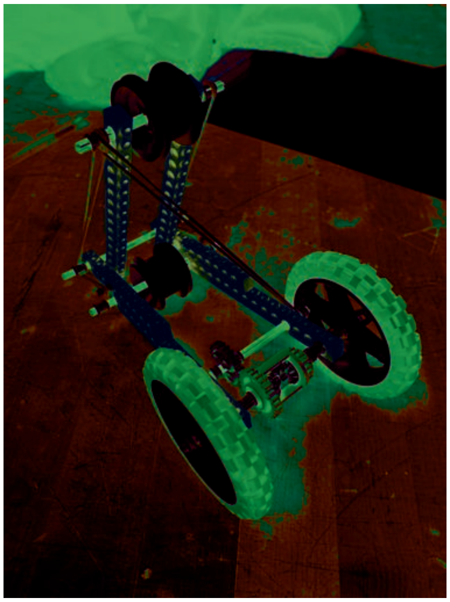
K_r	0.702	99.99 percent	table 15.3
K_ms	1.4	for non-idler	
C_S	0.85	surface Fig. 8.13	

Speed ratio	1.667

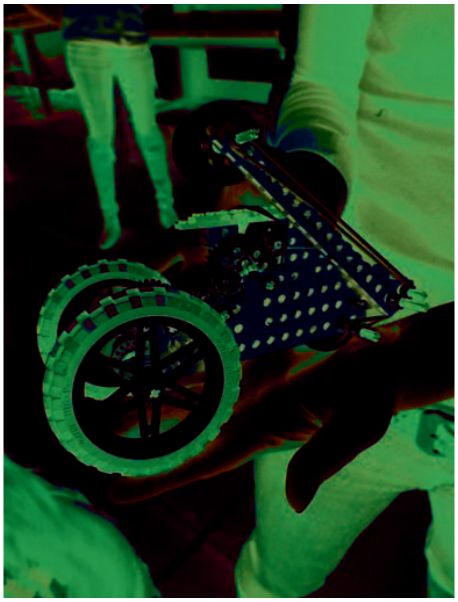
Contact Ratio Check		
r_b1	0.413	small base
r_b2	0.138	lg base
r_a1	0.476	(O.D./2)
r_a2	0.183	(O.D./2)
Center	0.586	
p_b	0.108	
dr1	0.237	
dr2	0.121	
C_Ratio	1.454	> 1 for load sharing

CRAWLER DESIGN ITERATIONS

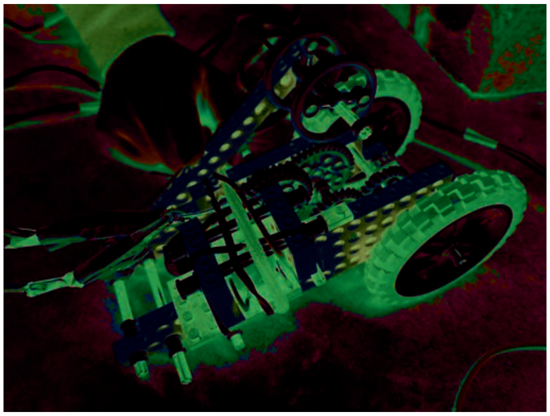
The Beginning



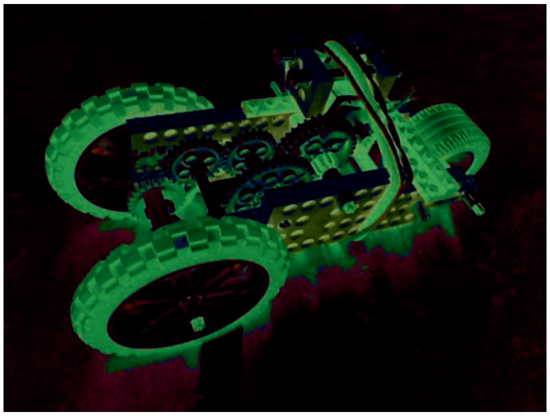
1. Used differential in hopes that it would help crawler turn.



2. Added gearing to differential.



3. Connected motor. Top arm hoped to help guide and push crawler up pipe.

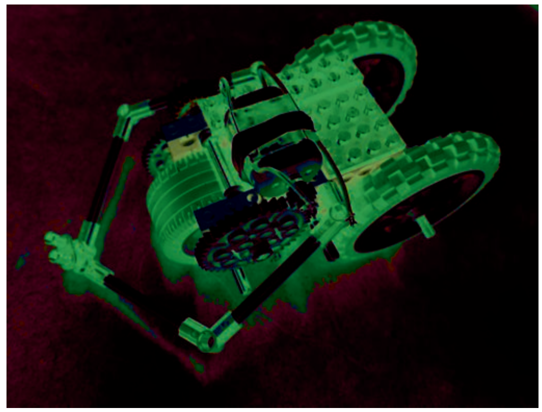


4. Played around with gear ratios, as crawler failed to move up pipe.

Design Review: In this first crawler, we attempted to drive the differential. However, the crawler refused to move, even with the new gear ratios.

Back to Basics

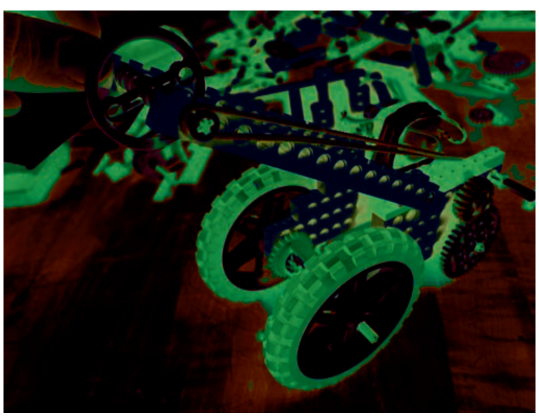
1. Made crawler more compact with gears on each side of driving wheel. This time differential not driven.



2. Front arms hopefully would help guide crawler.

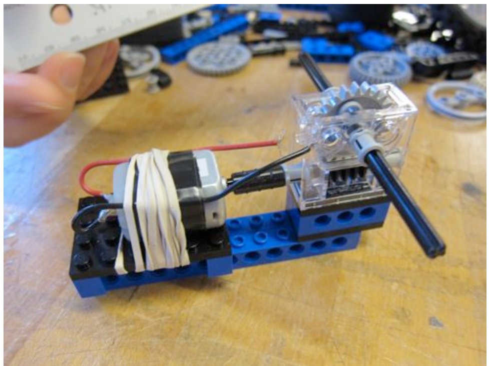
3. (bottom left) Top arm to help push crawler up pipe. Put in tension with rubber band.

4. (bottom right) Close up view of final design for this crawler.



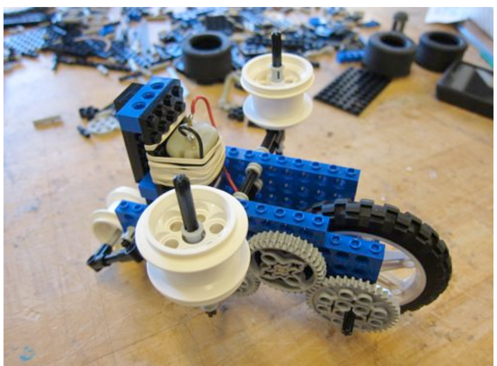
Design Review: This crawler was more compact, but had major issues with gear slippage when it made its way up most of the pipe. Its speed ascending was also quite slow.

Third Trial

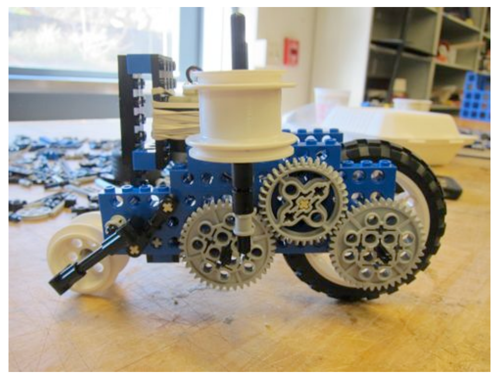


1. Took out differential. Worm gear for higher gear ratio and higher torque. Secure motor,

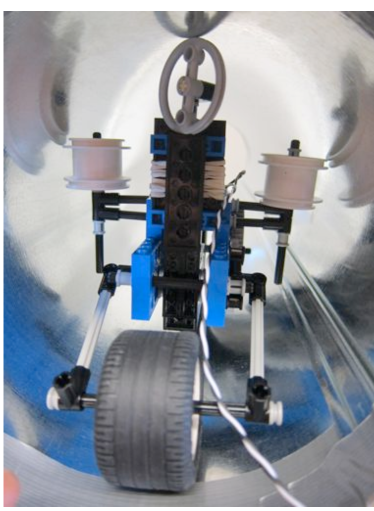
2. Add in wheels



3. Add in gearing. Side stabilizers. Change to just front driven wheel and back wheel

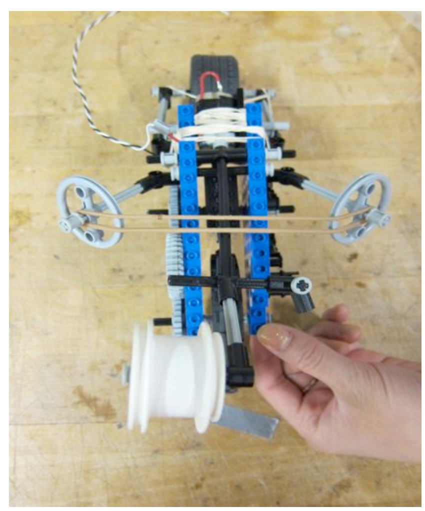


4. Close up side view on new gearing with worm gear

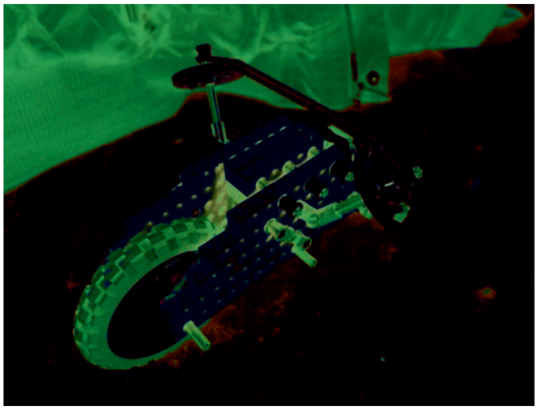


5. (left) Add in top wheel. Crawler still slips 3/4 way up tube

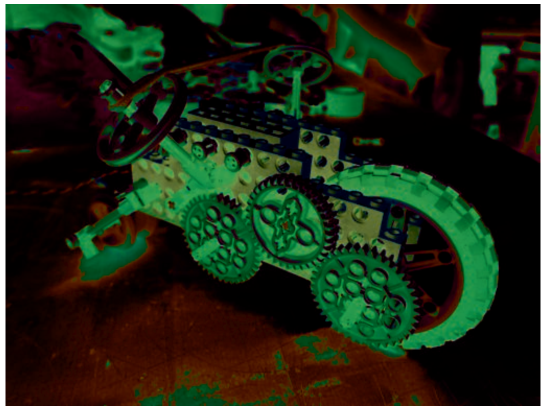
6. (right) Add side stabilizers and more surface area to top arm



Third Trial Cont.

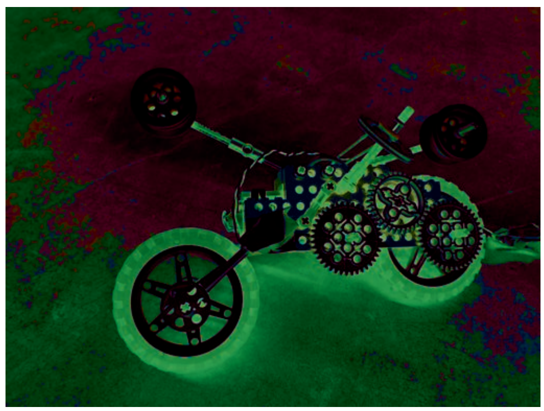


7. Removed top arm as it was creating drag. Secured motor tighter, as worm gear kept slipping out



8. Close up of new secured crawler with gears

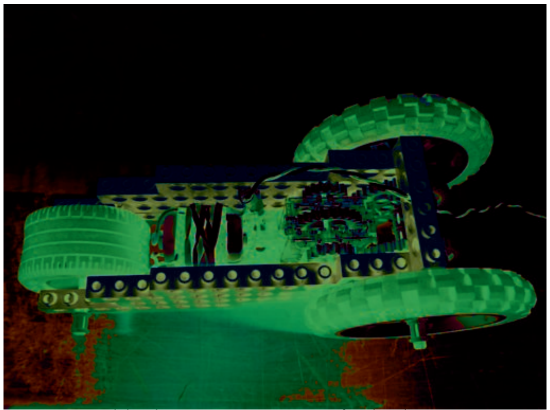
9. Changed back wheel to larger wheel--easy to become compact--thought it was interesting

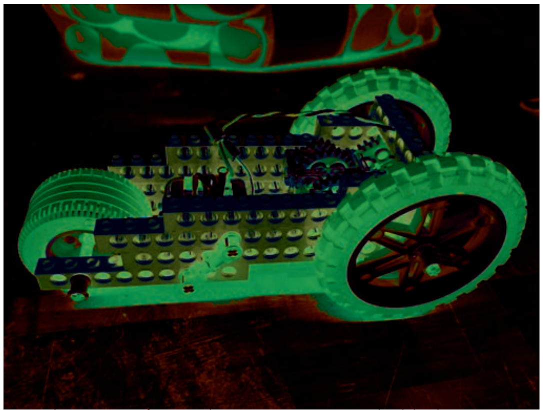


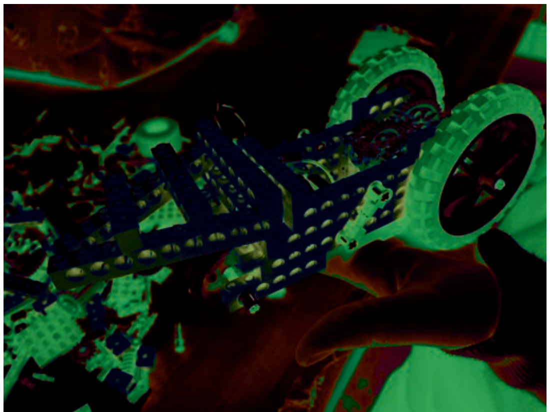
10. Added in additional stabilizers to keep crawler from tipping in pipe.

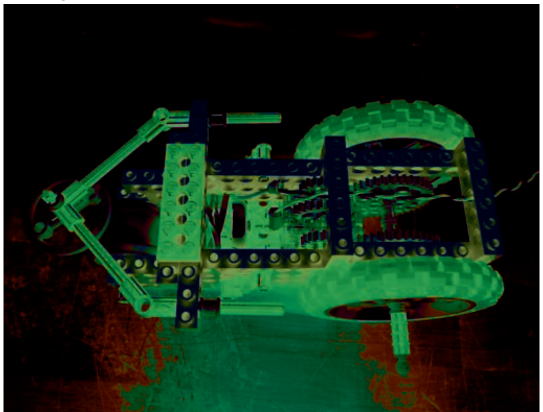
Design Review: As cool as this crawler looked, it was too long to make the 90 degree turns. This crawler also tended to tip or slide as it ascended the pipe. The top stabilizers, we realized were also creating a large drag, which made this version of the crawler move slowly up the pipe.

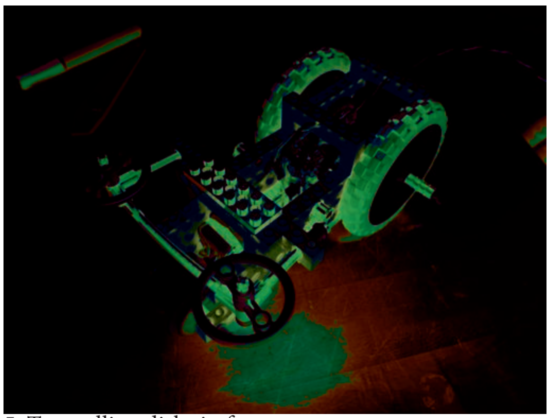
Final Iteration (Design Review in Write-Up)

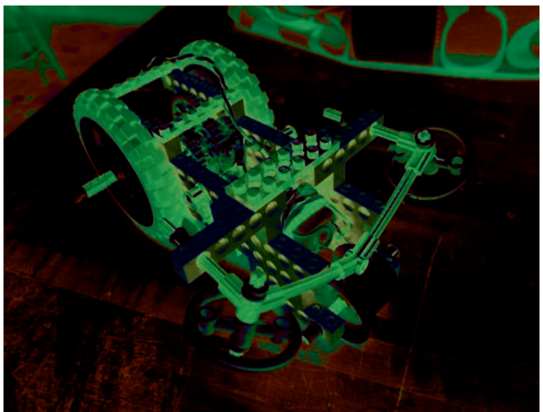

1. More stable design. Worm gear for higher torque.


2. Side View of new design. Front needed help getting through the turn.


3. Experimenting with the front section of crawler.


4. One rolling wheel in front with rolling disk.


5. Two rolling disks in front


6. Angled disks help navigate and turn more effectively