

PROJECT 1 - SAN BRUNO PIPELINE EXPLORATION
Crawler Documentation

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Team PipeRunner

Seth Winger

MK Li

Eirik Ravnan

Nicholas McGee

EXECUTIVE SUMMARY

We set out to create a crawler that could meet the basic requirements of our assignment: one that could move through a six-inch diameter replica of the ruptured San Bruno Pipeline, ascend a slope of approximately 20 degrees, and navigate both right-hand and left-hand turns while in the pipe. Rapid prototyping with the Lego kit we were given allowed us to create several initial designs quickly, and these swiftly converged to our final design. The final design was centered around two large rear drive wheels to provide the force that moved our crawler, angled front wheels on a rubber band suspension that allowed our crawler to turn and kept its center of gravity low, and a four-stage transmission to transfer power and torque from the motor to the drive wheels while providing a substantial reduction in angular velocity. We paid close attention to the project specification's additional constraints on crawler velocity and power usage as we continued to modify and fine-tune our final design. We aimed for an ideal crawler velocity, and after characterizing our motor this helped us determine that a four-stage spur gear transmission with an overall ratio of 81:1 would place us solidly in the best possible categories in terms of speed and power.

Our presentation went very well—we ascended the pipe at an average rate of 11.4 centimeters per second, and descended at 9.9 centimeters per second. We ran at an average of 3.75 volts while traveling uphill and 3.0 volts downhill, using a current of 125 and 60 milliamps, respectively. This gave us an average uphill power consumption of 0.47 watts and a downhill consumption of 0.18 watts. This power consumption placed Team PipeRunner second out of twenty-seven teams. Our design could be improved by lubricating the gears and especially the motor, as our motor seemed to be putting out less torque on presentation day than on the first day we tested.

BACKGROUND

On September 9, 2010, an aging thirty-inch steel pipeline in San Bruno failed catastrophically, as leaking gas erupted in a massive explosion that created a wall of flame 1,000 feet high, generated a shock wave as strong as a small earthquake, and ultimately left eight people dead. While pipelines like this are normally patrolled and inspected by large robots in a process called “pigging,” the age and sharp turns in San Bruno’s pipes prevented normal maintenance.

Our task was to design a quarter-scale Lego prototype of a robot that could navigate through the turns of San Bruno’s pipeline—specifically, one that could work its way up a 20 degree incline in a round pipe, through a 90 degree bend (either right or left), and then

be able to travel backwards out of the pipe without having to be turned around. The robot had to travel slow enough to capture reliable data about the pipe's welds, but fast enough to make inspection of miles of pipe viable. At our scale, this meant an ideal speed was around twelve centimeters per second. Furthermore, since the robot would not be attached to an external power source, it had to use as little power as possible to extend its life between charges, ideally below two watts.

And above all, it had to not get stuck in the pipe.

DESIGN

Chassis

A major concern from the onset of our designs was the weight of our crawler. To keep the power consumption under two watts, we knew we had to have a light crawler, yet it also had to be sturdy enough to hold the gears in place. We first attempted to design a crawler that used only light weight black Lego shafts (Figure 1), but discovered that the shafts were extremely flexible and that achieving correct gear alignment was almost impossible. This led to low efficiency at best at total separation of the drive train at worst.

All further prototypes were built with blue Lego beams, whose discrete nature allowed for easy gear placement. The final chassis includes a housing for the motor which secures the motor with a pressure fit, allowing us to easily adjust or remove the motor without compromising structural integrity or stability (Figure 2, next page).

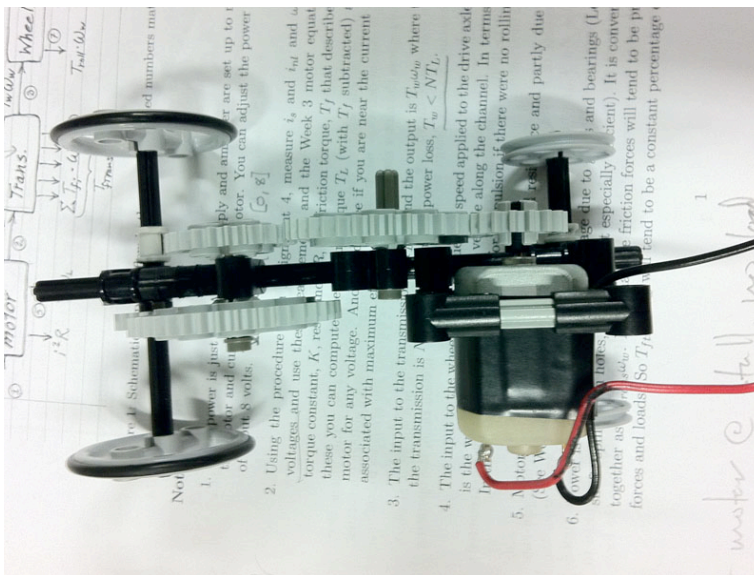


Figure 1: The original, shaft-based crawler

The chassis sits low to the ground and is constructed of very few pieces -- this both makes the crawler light weight and gives it a very low center of gravity (Figure 3, next page). The low center of gravity is especially important, as it helps prevent the crawler from spiraling up the walls of the pipe or from flipping over as it goes around the bend.

Rear Wheels

The force that propels our crawler up the pipe and around the bends comes from two large wheels mounted to a rear axle at the end of our gear train (Figure 4, next page). This configuration both moves the center of mass towards the drive wheels, as the large wheels are some of the heaviest parts of our robot, and provides the crawler with balance and stability by distributing its weight over a relatively wide space—much wider than the main body. The rubber tires have substantial friction against the steel pipe, and this allowed the crawler to create enough force to climb the incline inside the pipe.

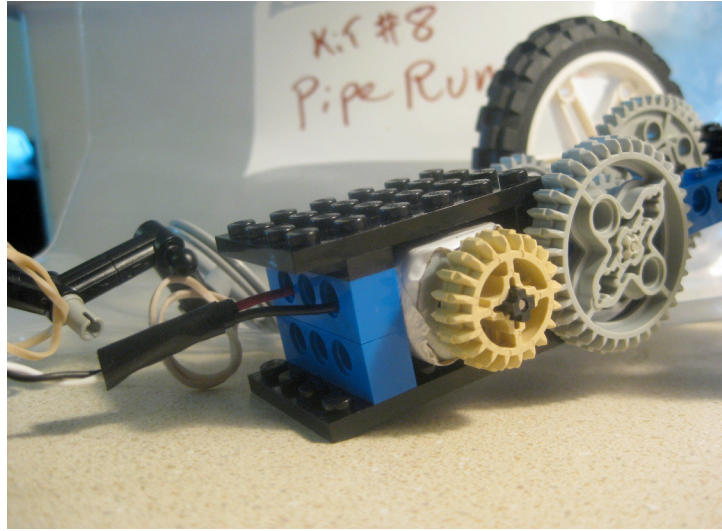


Figure 2: Motor housing (guide wheels removed)

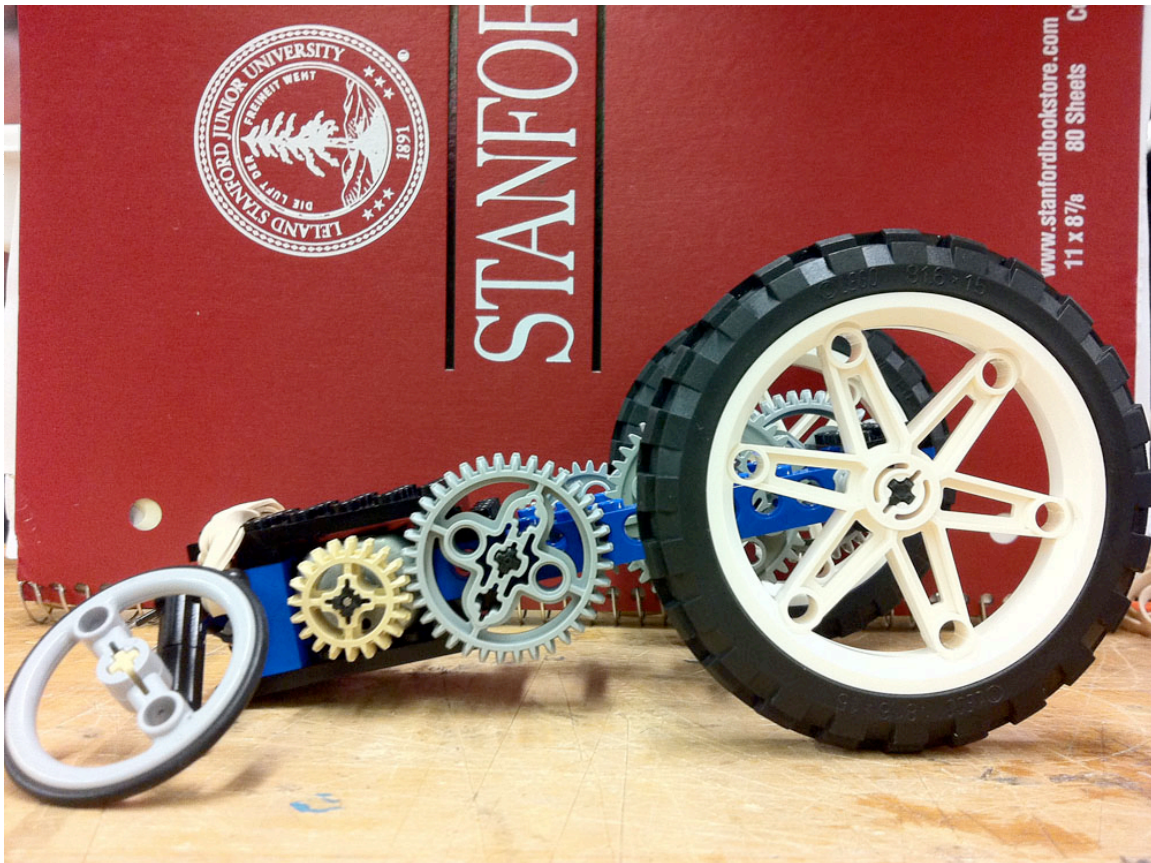


Figure 3: Complete chassis design. Note low center of gravity and lightweight construction.

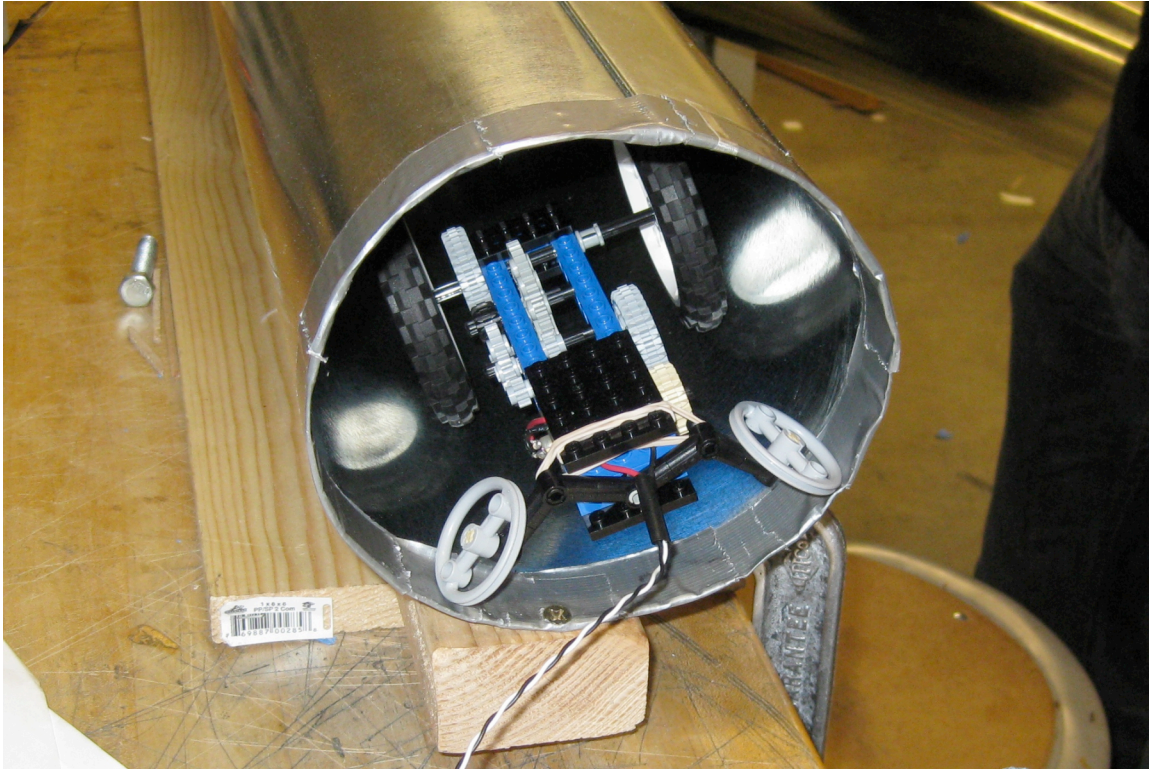


Figure 4: The crawler in the model pipe. The wide stance of the rear wheels helps provide stability and prevent spiraling.

Due to the large curvature of the pipe, we considered adding a differential to our rear axle, which would enable the left and right drive wheel to spin at different rates, allowing the crawler to move around the corner without one wheel slipping. However, adding the differential did not seem to improve our performance, instead increasing frictional losses and complexity, and so we reverted to the simpler straight axle.

Guiding Wheels

The main challenge we set out to tackle with the front guiding wheels was the bend in the pipe: how to ensure our crawler could successfully make it around the turn without flipping over, getting stuck, or otherwise failing disastrously. Our final design settled on small wheels with a large negative camber angle (Figure 5, next page), inspired by race cars built for cornering and the wheelchairs used in competitive paraplegic sporting events. Negative camber angles on tires tend to improve grip while cornering, which is exactly what we were looking for—though they do so at the cost of reducing straight-line acceleration (which did not matter in this application, as we were traveling at a slow, constant speed along the pipe).

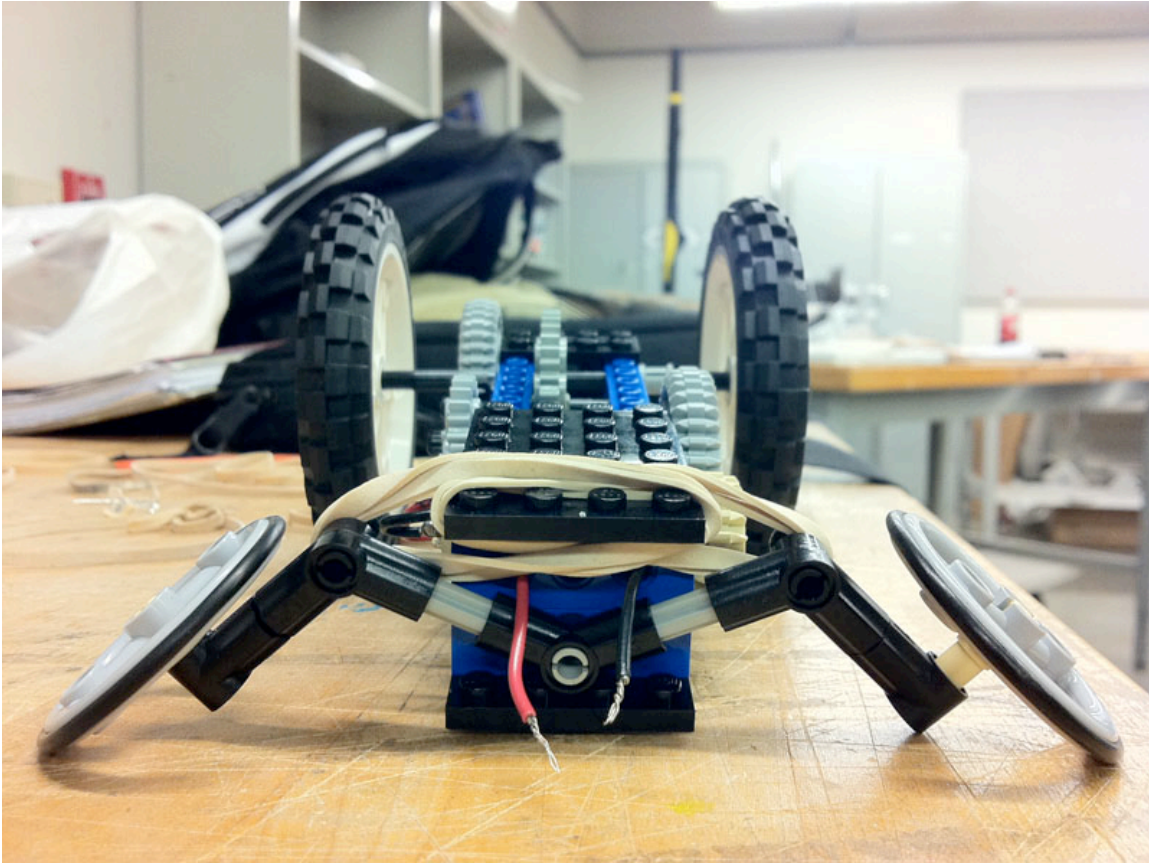


Figure 5: Large negative camber on the front wheels

An added benefit to the cambered front wheels was lowering the nose of our crawler, keeping our center of mass low. Placing the wheels to the side of the main chassis also allowed the crawler to rest against the sides of the pipe, not the bottom, increasing stability by spreading out the weight (cf. Figure 4).

The wheels were cradled in a suspension crafted out of two rubber bands. This flexibility helped the crawler traverse the ridges in the pipe without incident, much like an actual automotive suspension smooths out bumps in pavement.

Gear Train

Our first prototypes and tests showed that our crawler would need a very large speed reduction between the motor and drive wheels in order to meet the project's speed specifications. Nevertheless, we were leery of using a worm gear in our transmission, as we also wanted it to be as efficient as possible. These concerns led to our final four-stage transmission, which utilizes both the largest and smallest gears in our Lego kits and has an ultimate gear ratio of 81:1 (Figure 6, next page). Space constraints prohibited a higher

reduction, but by using only spur gears, we were able to keep our transmission efficiency very high while also creating a speed reduction high enough to travel at the ideal velocity of twelve centimeters per second.

The gears all fit onto a single pair of beams, which not only reduced the weight of our crawler substantially but also ensured that the spacing between the gears was optimized as much as possible.

Alternate Designs

Despite testing success with our two wheel drive design, we continued to pursue creative solutions to the pipeline-crawling problem. Our most fully developed device (Figure 7) widened our design horizons, but also created many new challenges which proved ultimately fatal to the project.

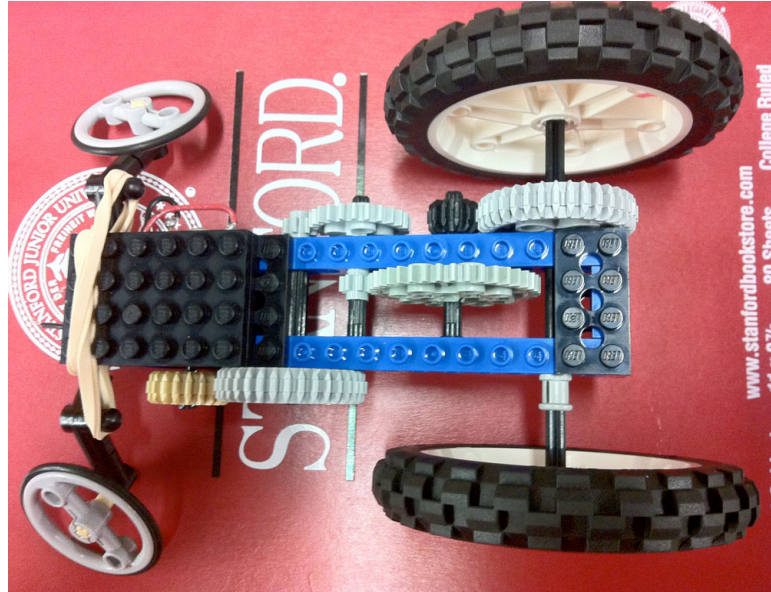


Figure 6: Four-stage gear train in the completed crawler.



Figure 7: The experimental unit, sporting an unbiased orientation drive system

The device was initially conceptualized as a test bed for several of the Lego transmission components we were unable to find uses for in our other design. We decided to try and develop a four wheel drive system which would maintain spring tension on the walls of the pipe in order to ensure that all drive wheels were constantly engaged. By creating a circular transmission, we attempted to address our largest risk factor in our primary design: flipping after riding up the side of the pipe. By engaging drive wheels with the top and bottom of the pipe constantly, any rotation of the unit would go unnoticed. However, we quickly learned that structural rigidity was critical to preventing the unit from twisting and becoming inoperable, yet at the same time this rigidity also prevented the flexibility necessary to traverse pipe bends. Problems continued to emerge, as we realized that the universal joints in the drive train did not deliver constant speed, and that if the wheels got out of alignment they would cause the drive train to lock up and contort the device. In the end, we decided that with more time and more sophisticated mechanisms this concept could prove superior to our primary design, but could not meet performance requirements with the resources or time at hand.

ANALYSIS of PERFORMANCE

Final testing produced great results. In the left tube our crawler ascended with 3.8 volts, using 0.12 amps over 7.5 sec, which is right at the goal speed of 12 centimeters per second. In the right tube we were slightly slower, running at 3.7 volts and using 0.13 amps over 8.3 seconds. The energy usage, where the energy was lost, and efficiencies can be found in Table 1.

	Left Tube (J)	Right Tube (J)	Average (J)	Efficiency
Total energy usage	3.42	3.99	3.70	12.08%
Energy lost in the motor	1.97	2.30	2.13	42.40%
Energy lost in the gears	0.21	0.25	0.23	85.47%
Energy lost in the bearings and due to rolling friction	0.61	0.71	0.66	50.62%
Energy lost due to slippage	0.06	0.07	0.06	91.03%
Energy lost due to other factors	0.12	0.22	0.17	n/a
Energy used by the crawler to climb	0.45	0.45	0.45	n/a

Table 1: Energy losses in the crawler

We calculated the efficiencies using several different techniques detailed in the remainder of this section, and with these efficiencies it was trivial to calculate how much energy is lost in each stage as losses accumulate.

Motor Efficiency

In order to find the motor efficiency, first we had to characterize the motor. The linear fits for our measurements of stall current and voltage can be seen in the left side of Figure 8, and the results from our no load tests can be seen on the right side.

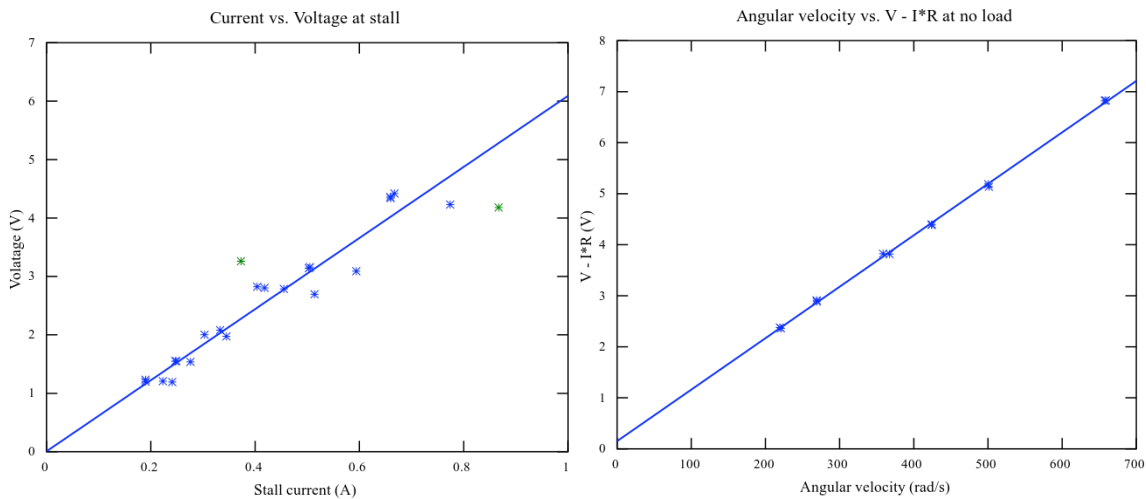


Figure 8: Characterization of the motor. Linear fit of the stall tests on the right and of the no load test on the right.

From the linear fits we found that the motor resistance was 6.09 ohms, the motor constant, K , was 0.010 N·m/A, and the friction torque in the motor was approximately 0.575 mN·m for our operating range. These values allowed us to calculate the torque, speed, power and efficiency of the motor, and the relationships we obtained are plotted in Figures 9 through 11.

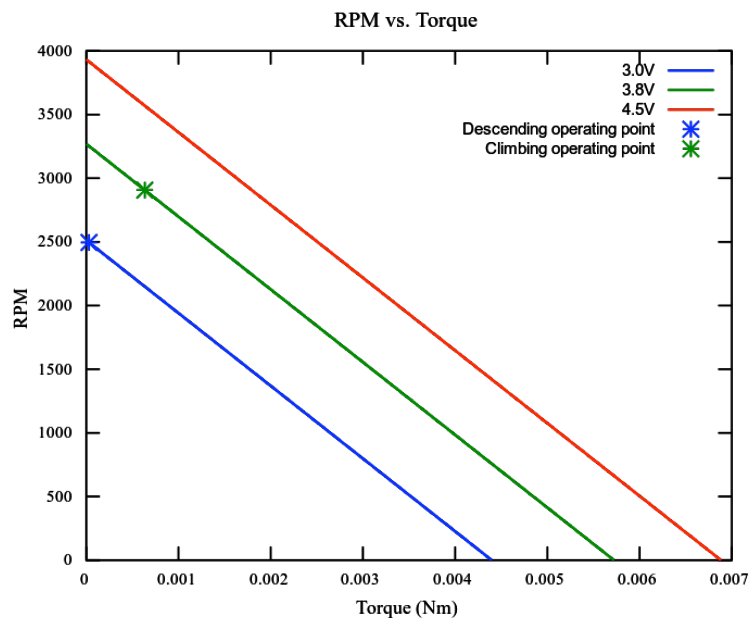


Figure 9: Speed in RPM of the motor shaft versus the motor torque

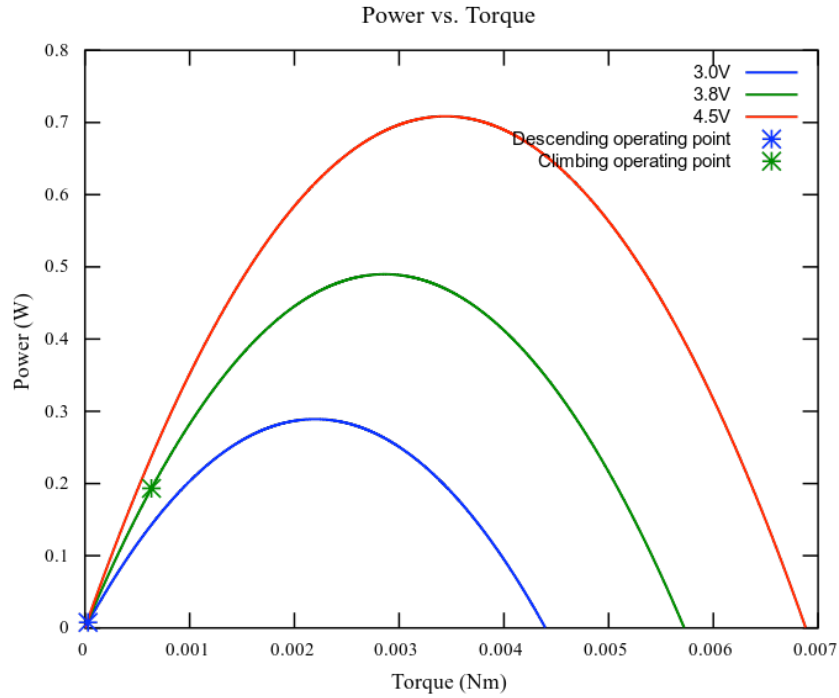


Figure 10: Output power of the motor versus the motor torque.

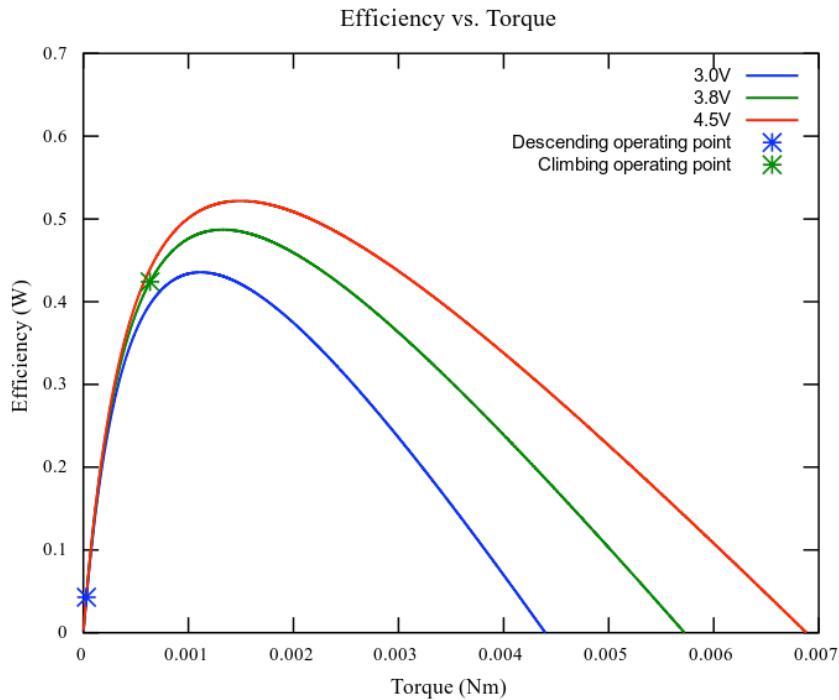


Figure 11: Output efficiency of the motor versus the motor torque.

From testing we found that we need to run at about 3.7 volts and a current around 0.125 in order to have a speed of 12cm/s. At these operating conditions the motor gives us an efficiency of $\eta_{motor} = 42.40\%$. Thus with a total input energy of about:

$$3.8 \text{ V} \times 0.12 \text{ A} \times 7.5 \text{ s} \approx 3.42 \text{ J}$$

The energy loss in the motor is about:

$$3.42 \text{ J} \times (1 - 0.424) \approx 1.97 \text{ J}$$

Gear Efficiency

By finding the force needed to pull the crawler with and without the gears engaged, we approximated the gear efficiency. We did this by having a mass pull the crawler up the test section at approximately 12 cm/s, finding that it takes 100 grams to pull the crawler without the gears engaged and 117 grams with them engaged. Thus assuming there is negligible slipping during the testing we get that:

$$\eta_{gears} = \frac{P_{no\ gear}}{P_{gear}} = \frac{m_{no\ gear} \times g \times v}{m_{gear} \times g \times v} = \frac{m_{no\ gear}}{m_{gear}} = \frac{100\ g}{117\ g} \approx 85.47\ %$$

where

- η_{gears} is the gear efficiency
- P_{gear} and $P_{no\ gear}$ is the power needed to pull the crawler up the tube with and without the gears connected, respectively
- m_{gear} and $m_{no\ gear}$ is the mass needed to pull the crawler up the tube with and without the gears connected, respectively
- g is the gravitational acceleration (9.81 m/s^2)
- v is the velocity of the crawler (12 cm/s)

This then leads to an energy loss in the gears of about:

$$3.42 \text{ J} \times 0.424 \times (1 - 0.8547) \approx 0.21 \text{ J}$$

Rolling and bearing efficiency

By comparing the force we found it takes to pull the crawler up the tube without the gears engaged to the force it would take without any losses we can find approximately how much the losses due to rolling friction and friction in the bearings amount to. The mass of our crawler was 148 grams, and thus the minimum force required to lift it up the pipe is:

$$F_{min} = mg \sin(\theta) = 0.148 \text{ kg} \times 9.81 \text{ ms}^{-2} \times \sin(20 \text{ deg}) \approx 0.497 \text{ N}$$

where

- F_{min} is the minimum possible force needed to make the crawler go up the pipe
- m is the mass of the crawler
- g is the gravitational acceleration (9.81 m/s²)
- θ is the angle of the pipe (20 deg)

Giving us an efficiency of:

$$\eta_{roll} = \frac{F_{min}}{m_{nogear} \times g} = \frac{0.497 N}{0.100 g \times 9.81 m/s^2} \approx 50.62 \%$$

where η_{roll} is the rolling and bearing efficiency, and an energy loss of:

$$3.42 J \times 0.4240 \times 0.8547 \times (1 - 0.5062) \approx 0.61 J$$

Contact efficiency

Since we do not have a perfect contact with the ground there will be some slippage and this we can calculate by using the following formula:

$$P_{slip} = \tau_{wheels} \times \left(\omega_{wheels} - \frac{v}{r_{wheels}} \right)$$

where

- P_{slip} is the power lost due to slippage
- τ_{wheels} is the torque of the wheels after rolling friction is subtracted
- ω_{wheels} is the angular velocity of the wheels
- v is the linear velocity of the crawler (12cm/s)
- r_{wheels} is the radius of the wheels (4.1cm)

Therefore the efficiency of the contact with the ground is:

$$\eta_{contact} = 1 - \frac{P_{slip}}{P_{wheels}} = 1 - \frac{\tau_{wheels} \times \left(\omega_{wheels} - \frac{v}{r_{wheels}} \right)}{V_{in} \times I_{in} \times \eta_{motor} \times \eta_{rolling} \times \eta_{roll}} \approx 91.03 \%$$

where

- $\eta_{contact}$ is the contact efficiency of the wheels

- V_{in} is the voltage supplied to the motor
- I_{in} is the current supplied to the motor

Thus there is an energy loss of:

$$3.42 J \times 0.4240 \times 0.8547 \times 0.5062 \times (1 - 0.9103) \approx 0.06 J$$

Other factors

Finally, other unaccounted for factors like air resistance or the difference in gear loading when the crawler is driven compared to when we back drive it. We can calculate these losses by comparing the minimum power needed to climb to the actual power that we have left after the other losses. The energy loss in this stage for the left tube was 0.12 J.

GEAR TRAIN REDESIGN

Our gears performed very well due to the accurate spacing we got from the Lego bars. An efficiency of 85% without using any lubrication is quite remarkable, so we would certainly keep the linear gearbox with accurate spacings. What we could change in future designs is the input voltage and the gear ratio; however, assuming the losses through the gears and drive train stay the same and the slippage is the same, we still need the same amount of output power from the motor in order to maintain a speed of 12 cm/s. In the left tube during our final presentation, the output power of the motor was 0.193 N·m, and in Figure 12 the motor efficiency is shown for different voltages running at this power.

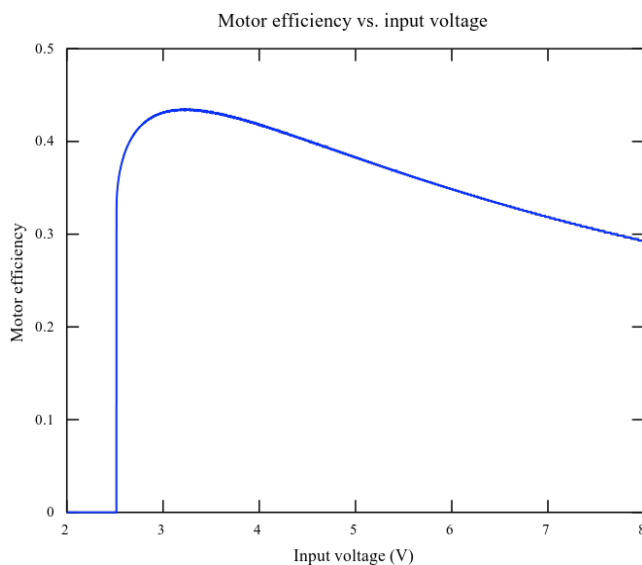


Figure 12: Motor efficiency when running at a output power of 0.193 N·m with varying voltage

This plot shows the maximum efficiency our motor could have achieved is 43.43%, which occurs at a voltage of 3.23 V.

The next question is then what gear ratio must the crawler have in order to be able to run at this power climbing up pipe. Figure 13 (next page) shows the relationship between voltage and gear ratio at the specified running power. From this we can determine that the optimal gear ratio for our crawler is 79.988:1.

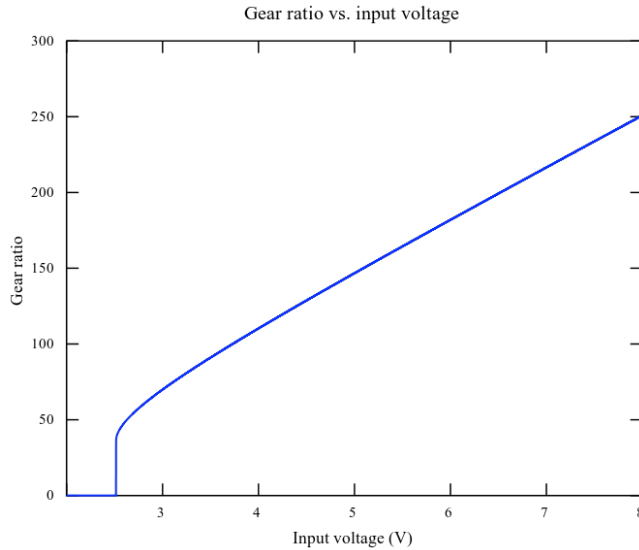


Figure 13: Gear ratio needed for peak efficiency with varying voltages.

This is remarkably close to our gear box with a ratio of 81:1. Our gearbox had the following tooth ratios in each stage:

36:20, 24:8, 40:8, 36:12

If we could make customized Lego gears, we could have swapped two of these, making the gear ratios:

36:20, 25:8, 38:8, 36:12

Or an overall ratio of 80.156:1.

We would have been closer to the maximum, but with our Lego gears it would be really hard to make a better gear box. One other option is to change the size of the wheels, since the wheel size is essentially an extension of the gearbox. If we had put rubber bands around the wheels, for instance, we might have been able to get a higher efficiency, but this would also add weight. Adding or removing gear stages will not gain much in terms of efficiency as the gears will have poor contact ratios if we remove a stage and more friction if we add one.

ANALYSIS of GEAR STRESS

Based on the mass of our vehicle and the operating torques and speeds reached in tests, durability of the gears in the drive train does not appear to be a limiting factor in performance. However, we performed a stress analysis in order to ensure reliable performance in real life applications. To obtain valuable data, some assumptions had to be made:

1. Lego gears can be assumed to have similar wear properties to ABS plastic
2. The gears have an AGMA quality of 8, pitch angle of 20°, and pitch of one tooth per millimeter
3. Stresses on the crawler will not exceed those experienced in tests
4. Worst-case ultimate stress at high fatigue can be approximated as $\frac{S}{S_u} = 0.5$.

Given that the final robot will be operating on battery power, we can calculate a reasonable lower bound for the number of cycles the gears are expected to run reliably. If the machine runs on 2×18650 lithium ion cells in parallel (generating 3.7 V), it will have an available 5200 mAh. Running at 120 mA and approximately 3000 RPM, the input gear will experience approximately 8×10^6 cycles, while the wheels will experience only 3.6×10^4 cycles. Since the wheels are where stresses will be highest, assumption #4 seems reasonable.

Given these assumptions we established the following initial parameters:

Ultimate Stress of ABS Plastic (S_u)	34.47 MPa
Fatigue Life Safe Stress (S_n)	17.23 MPa
Input RPM (max)	3000 RPM
Input Torque (max)	.0007 N·m

The first step to ensuring proper wear patterns was to calculate contact ratios for all four stages using the Contact Ratio equation:

$$CR = Z / P_b$$

where

- Z is the distance travelled by each contact point along the line of action
- P_b is the distance between contact points

After determining that the Contact Ratios were acceptable (see Table 2 for results), we were able to calculate an approximation of the maximum stresses on each tooth using the Lewis/AGMA bending stresses equation:

$$\sigma = F_t * P * k_o * k_v * k_m / (b * J)$$

where

- σ is the Lewis stress
- F_t is the tangential force on teeth
- P is the pitch of gear
- k_o is the overload factor (1.3 for our drivetrain)

- k_v is the velocity factor (see Table 2)
- k_m is the mounting quality (assume the ideal case, 1.3)
- b is the face width (3-4 mm for Lego gears)
- J is the Lewis geometry factor (See Table 2)

At this point it had been determined that our gears would easily operate within safe parameters (again, see Table 3 for final results) , but we chose to do one more calculation to ensure that we had an accurate approximation of safe stresses, using the Moore Test:

$$S_u = S'_u * C_G * C_S * k_r * k_t * k_{ms}$$

where

- S_u is Moore's ultimate stress
- S'_u is the fatigue life safe stress
- C_G is the gradient factor (.85 since pitch is less than face width)
- C_S is the surface factor (1 for our high-quality Lego gears)
- k_r is the reliability factor (.814 for 99.999% certainty)
- k_t is the temperature factor (1 in our operating conditions)
- k_{ms} is the mean stress factor (1.4 for non-idler gears)

We are confident that the gears will provide reliable service for many megacycles.

	Stage 1	Stage 2	Stage 3	Stage 4
Face Width (mm)	4	3	3	4
k_v	1.016	1.007	1.004	1.002
$V_t (m/s)$	3.14	.698	.233	.070
CR	1.625	1.454	1.510	1.556
$\tau_{max} (N*m)$.0013	.0038	.0189	.0567
$F_{t,max} (N)$.07	.315	.945	3.15
$\sigma_{max} (MPa)$ [1 st gear, 2 nd gear]	.0884, .0791	.8513, .5959	2.546, 1.573	6.352, 3.8114
$S_u (MPa)$	13.52	13.52	13.52	13.52

Table 3: Results of Tooth Stress Analysis

Stresses in even the later stages do not exceed 50% of our ultimate stress estimate. This is, in fact, a conservative estimate, as some sources put the ultimate strength of unfatigued ABS at nearly 50 MPa. We believe that reliability is further improved by our use of wider gears at the motor input stage (where cycles are highest) and at the final stage (where stresses are highest). In these circumstances, our crawler could be expected to run for 43 hours without a recharge, with 99.999% certainty that the system would not fail. During that time, it would travel at least 18.5 km.

CONCLUSIONS

In terms of power consumption, bend navigation, and climbing speed, our crawler was remarkably successful. Its success is largely due to the lightweight design of the chassis, which was also stable enough to mount the motor and gears to easily and efficiently. Large back wheels increased stability and allowed the crawler to exert more force as it moved uphill, small front wheels with a large negative camber and rubber band suspension helped the crawler corner smoothly, and an incredibly efficient gear train improved overall efficiency and performance dramatically. We were happy with our decision to eschew a worm gear in favor of a four-stage spur gear transmission, which increased efficiency and made mounting to our frame simple and straightforward. Though we met all the stated project requirements, to improve our crawler's performance, we would lubricate the gear train and the motor in order to reduce frictional losses from the bearings. With this improvement, we believe our crawler is ready to patrol the pipelines of San Bruno and beyond.