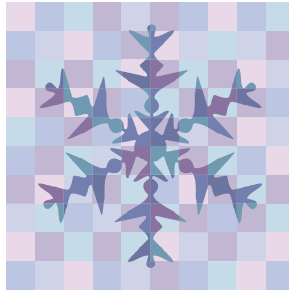


Energy Efficient Snow Diversion & Accumulation Prevention Device



Major Qualifying Project
Submitted to the Faculty of
Worcester Polytechnic Institute
in partial fulfillment of the requirements for the
Degree in Bachelor of Science
In
Mechanical Engineering
By Nithin Das



Date: 4/27/2016
Mechanical Engineering Department
Project Advisor: Pratap Rao

Professor Pratap Rao, Advisor

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Abstract

This MQP presents a solution to the time consuming and expensive process of snow removal. Eleven initial designs were generated and analyzed in terms of forces, weight, cost, safety, energy efficiency, storage/installation and internal forces. Finally a cable guided shovel design was selected for further analysis, design refinement and prototyping. The final design consists of a shovel that is driven along taut cables fixed parallel to the path to be cleared. The cables pass through either side of the shovel and through a motor-pulley assembly mounted to the shovel. Opposing frictional forces on the shovel blade and cable were determined to size the motors and cable. A prototype device was assembled to test its performance using mulch as the substitute for snow.

Acknowledgements

The project was possible only due to the support of my Parents and Sister. And my Project Advisor, Professor Pratap Rao for his guidance and insight all along the way. Also I would like to thank my friends Nathan, Kevin, and Edson and William for their help in understanding and obtaining parts for this projects as well as helping me brainstorm.

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Chapter 1: Introduction

I proposed this project for my MQP in A Term of 2015 to Professor Pratap Rao. It was accepted as a 3 term MQP that lasted through B, C, and D Term. I wanted to work on a snow accumulation prevention device because of the realization of the crippling impact that a strong snow season could have on busy families. Just the task of shoveling out of your driveway everyday if you have a busy schedule can be a highly inconvenient and a morale draining task, especially first thing in the morning. It can also be a financial burden on families with low income when heating oil bills are already so high. The initial goal was to design a device that cleared a path continuously using air flow, but that idea was changed to a cable guided shovel that oscillated on the driveway in regular intervals. Much later in the project I realized that the automation aspect of having the device oscillate on the driveway was a coding intensive task so it was discontinued. Also, the cable guided shovel required a “snow flipping device” that does the job of transferring the shoveled snow off the edges of the driveway, however the design and mechanics of that part was not pursued due to time constraints. Thus this report concentrates mainly on the snow moving part of the assembly.

As one goes through this report it is important to remember that it is laid out in a chronological order, so as calculations are being done, the designs, clearing path, method of implementation, etc. undergo changes until the “Testing Setup” section. Many of the calculations were done in inches during setup therefore you might notice a lot of non-rounded SI approximations. An acronym that you will come across in later sections is CGA which is short for Cord Gripping Assembly. In the beginning of this project I referred to the Shaft Collars as pulleys because initial designs were drafted in that manner. However during prototyping, VEX parts were used for implementing the CGA and shaft collars were used instead of pulleys.

Chapter 2: Identification of Need

The winter of 2014-2015 was a particularly harsh winter with Worcester City regaining the title of Snowiest City in America (Telegram-Staff). Worcester received about 115.6 inches of snow(~ 9.6 feet). This translates to a lot of energy, time, and safety risks taken to clear snow from roads and buildings. For example, the cost of clearing driveways alone in the 2014-2015 season would have reached about \$700 at \$35 per service for 20 snow days.

Snow blowers are effective, but heavy and cumbersome to be used easily by everyone. If there is a strong wind, the snow that is being blown ends up in the user's face, which can be very uncomfortable. There are also maintenance costs (spark plug, oil, tires) and operating costs (gas, battery). They are expensive and wear being exposed to the elements and varying temperatures. Snow ploughs are fast and sometimes the only option in case of heavy snow fall. Each cleaning service is about \$35 dollars and if there are 20 snow days, that is, a total of \$700.00 spent on snow removal for one winter season. For many middle income households, this is just another unnecessary burden on top of other bills.

Shoveling by hand is very hard especially with wet snow. It is really backbreaking work that is time consuming, and can only be done by people who are physically capable of doing so. Others would have to call a cleaning service.

Finally, road salt is effective only for light snowfalls, not for heavy storms. Also, they are known to have bad effects on waterbodies and vegetation.

Thus the need boiled down to a device that can keep snow from preventing snow from accumulating on asphalt surfaces, in an energy efficient manner, that does not use road salt or melting solutions.

Chapter 3: Background Research

Methods of snow removal other than shoveling, ploughing, snow blowing, water spraying or salting are presented below.

1) Electric Radiant Heat Mats and Wires by Warmly Yours



Figure 1 - Heating Elements By Warmly Yours

The wires are laid under concrete, asphalt, or pavers and heat is conducted through the wires to the surface of the material. As expected this is method takes long to conduct heat to the surface so its not a instant solution. The standing water can cause a lot of water damage on the pavement which can be harmful.

Cost: more than \$5000.00 for 33'X 18' driveway wiring (for heating circuit parts only, does not include pavers, asphalt or concrete and labor costs. Grand total might be \$10,000) (WarmlyYours, 2015)

2) Carpeted Snow melting heat mats by HeatTrak



Figure 2 - Heating Mats by HeatTrak

This is a mat that is laid on top of any given surface to melt the snow. There is no installation required. The mats are made of an electrically operated heating element placed between two surfaces of non-slip rubber.

Cost: \$10,700 for a 33'X18' area mats (cannot be used as a driveway mat, because it is stated on the website that: We do not recommend the mats for parking lots or any other driveway that has a lot of vehicular traffic) (HeatTrak, 2015)

3) Japanese Road Sprinkler Systems (Tajima, Japan):



Figure 3 -Road Snow Melting System Tajima

Water is sprayed on the road to melt the falling snowflakes (perspectivedetective, 2009); however this system cannot be applied in New England, because this system is meant for warmer climates. Whereas if it were used in New England, ice would form once the temperature falls. The average low temperature rarely goes below freezing in Tajima, whereas in Massachusetts, below freezing temperatures in the winter months is a normal occurrence

- Weather data Tajima
<http://www.worldweatheronline.com/v2/weather-averages.aspx?q=TJH&tp=1>
- Weather data Massachusetts:
<http://www.usclimatedata.com/climate/worcester/massachusetts/united-states/usma0502/2015/1>

Apart from the aforementioned solution there were no intrinsically different designs in the market or in any existing patents. This meant that the existing solutions would not be energy efficient, cheap, easily operable, or environmentally safe.

Therefore a completely new design based on the concept of keeping the snow from settling on the ground in the first place was pursued. Two major areas of research that helped this endeavor was the ice resistant nanomaterial panels and air flow. The nanomaterial panels were based on the design of the slippery sides of the pitcher plant. Liquids surrounding the nanostructures on the side of the plant create a slippery surface that helped the plant obtain its food. This idea was being pursued at MIT who had engineered a superhydrophobic surface which repels water (Bullis, 2014). Although this idea was very interesting, the practicality of obtaining and paying for such expensive panels that are not widely marketed was simply out of the budget allotted for this project.

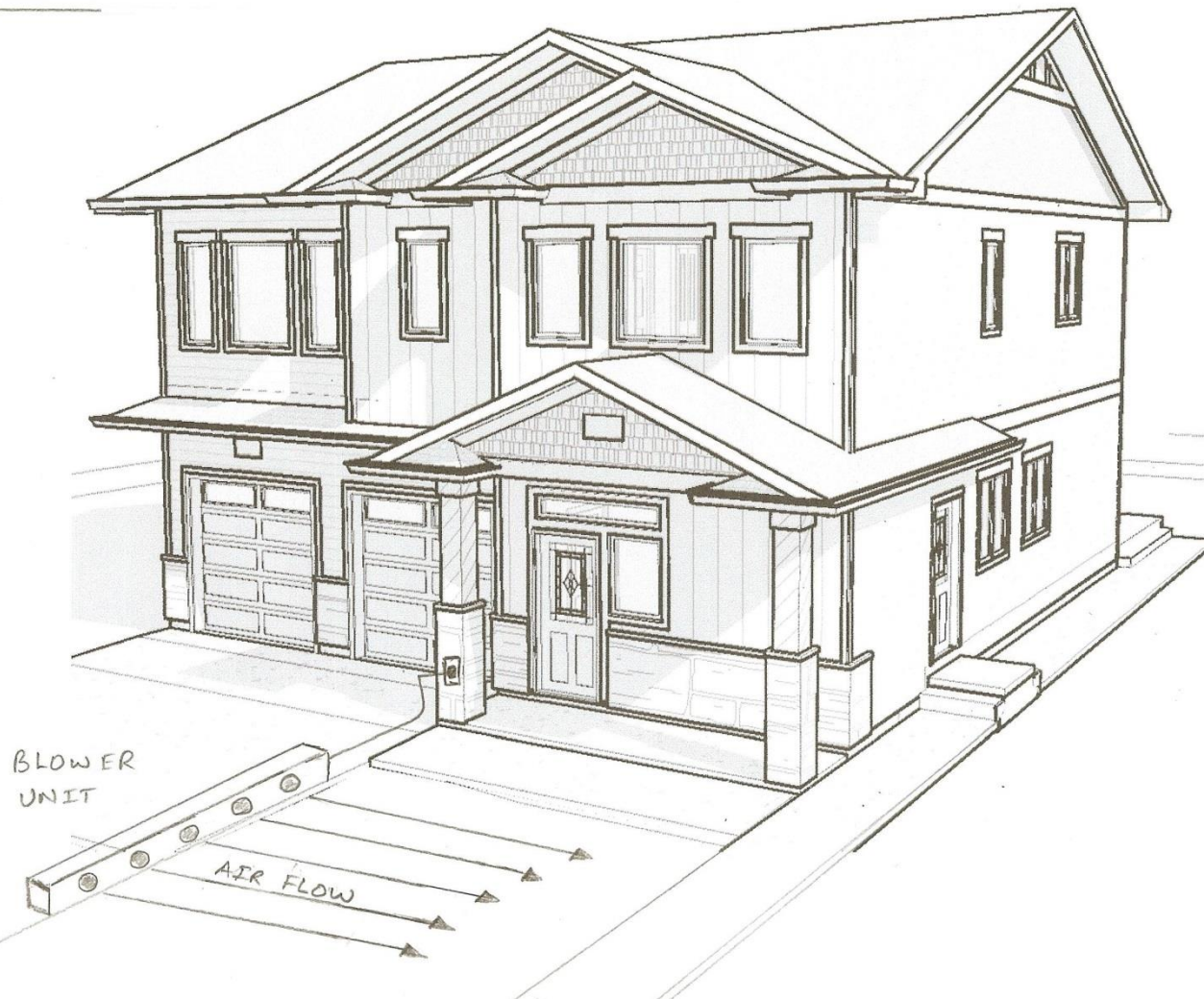
Therefore it was decided that it would be best to proceed with the air flow design. This design involved the use of a strong laminar airflow over a driveway surface. The laminar air flow would be blown along one side of the driveway. As the layer of air flowed across the width of the driveway, it would act as a conveyor belt which takes the falling snow and deposits it on the other side of the driveway. This requires then that there be some allotted area on at least one side of the driveway that the snow can be transferred to. The following section details the preliminary designs.

Chapter 4: Preliminary Designs

4.1 Design 1 - Blower with Axial Fans

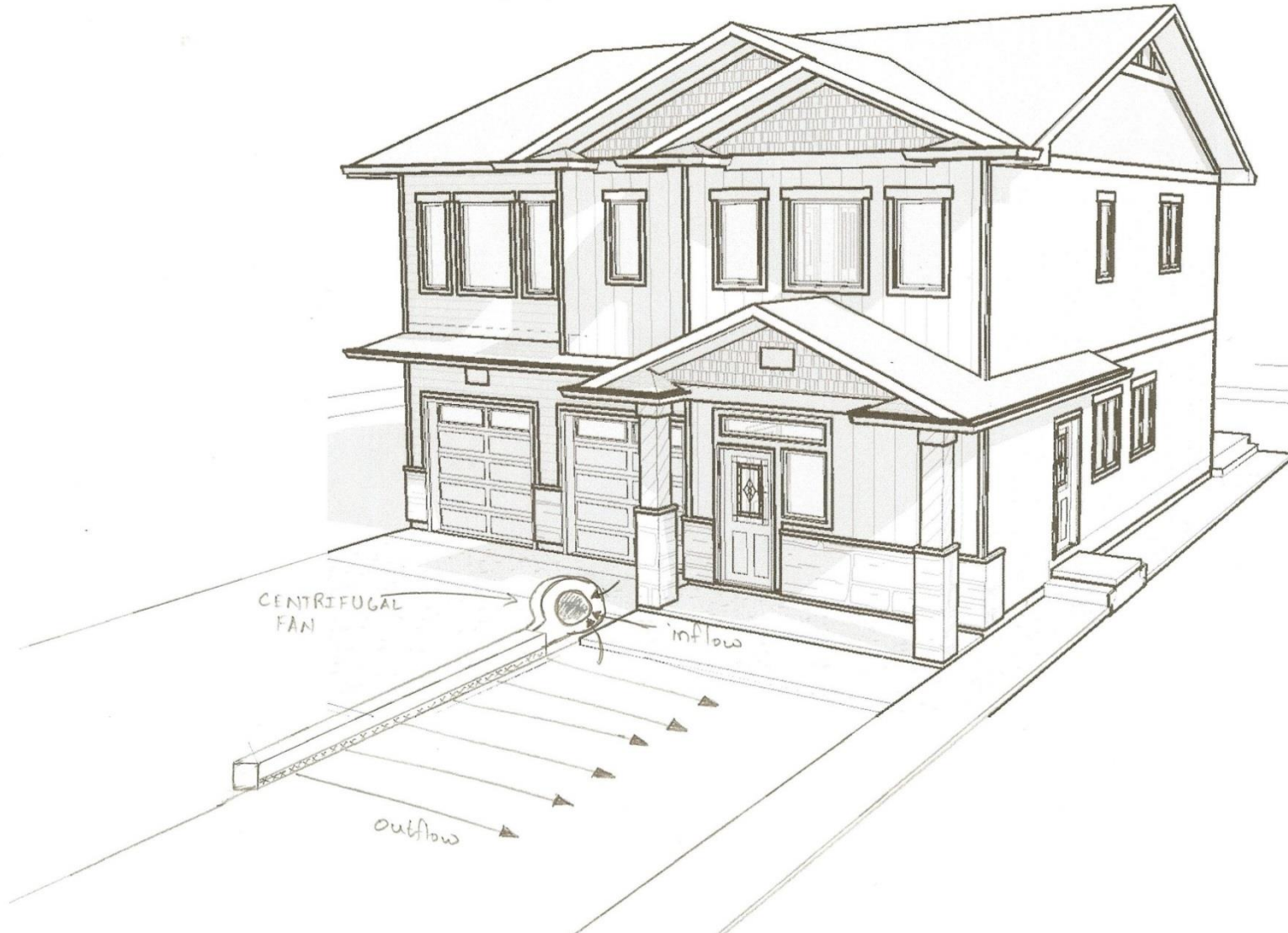
BLOWER UNIT
w/ AXIAL FANS

DESIGN 1



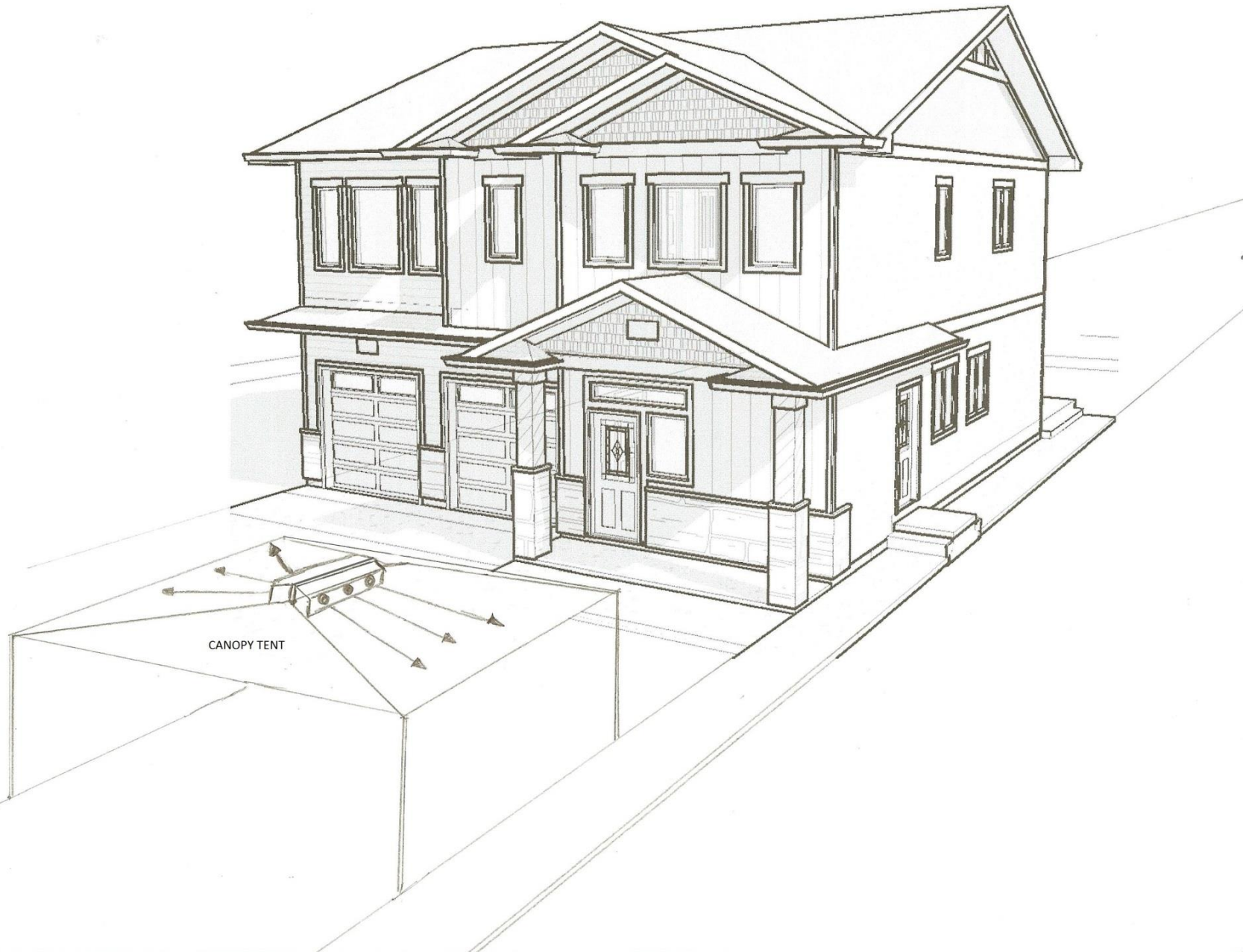
CENTRIFUGAL FAN

DESIGN 2



4.3 Design 3 – Blower on Tent With Axial Fans
BLOWER ON TENT-AXIAL FANS

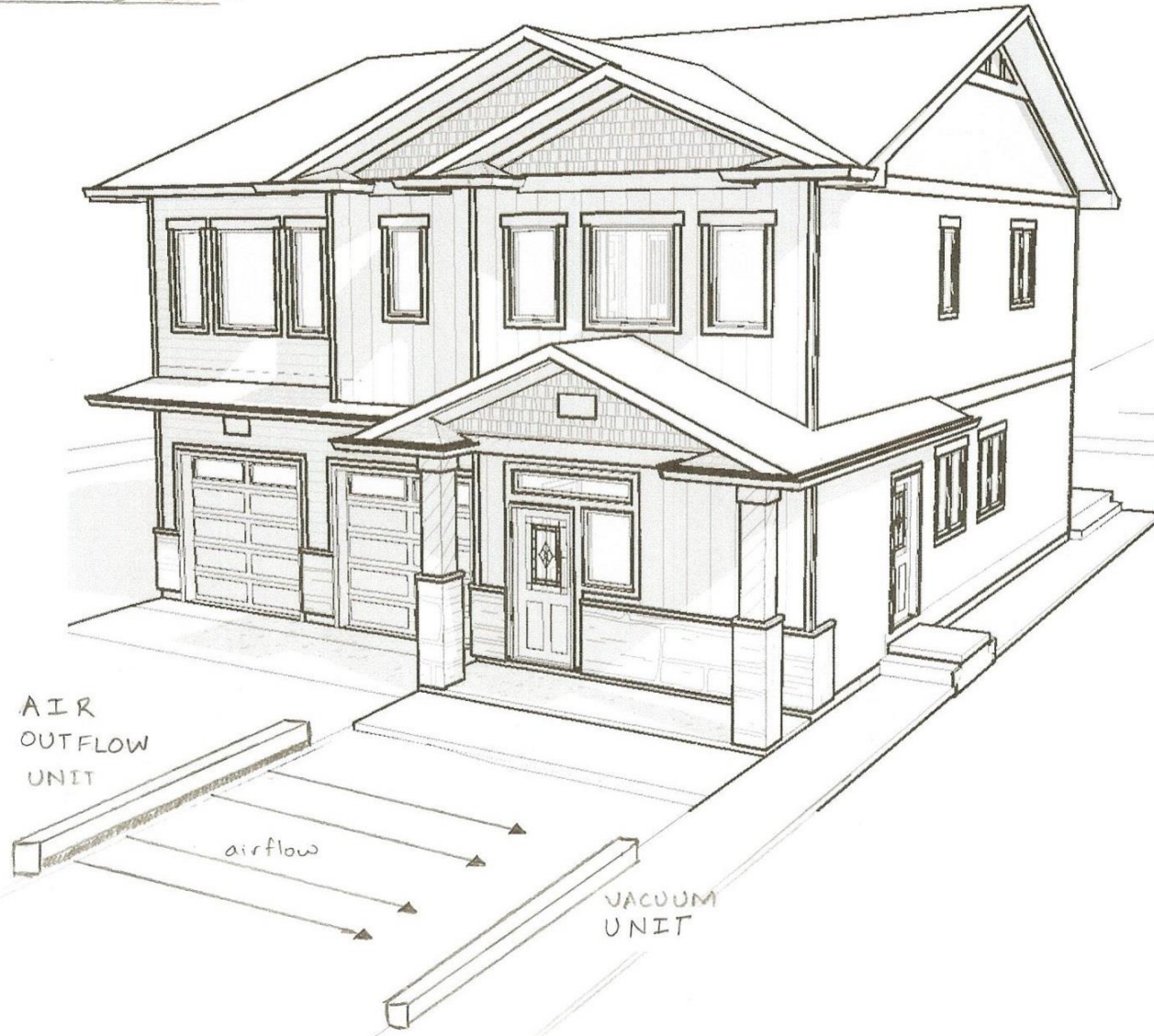
DESIGN 3



4.4 Design 4 – Cyclical Flow Unit With Underground Blower

CYCLICAL FLOW UNIT
W/ BLOWER UNDERGROUND

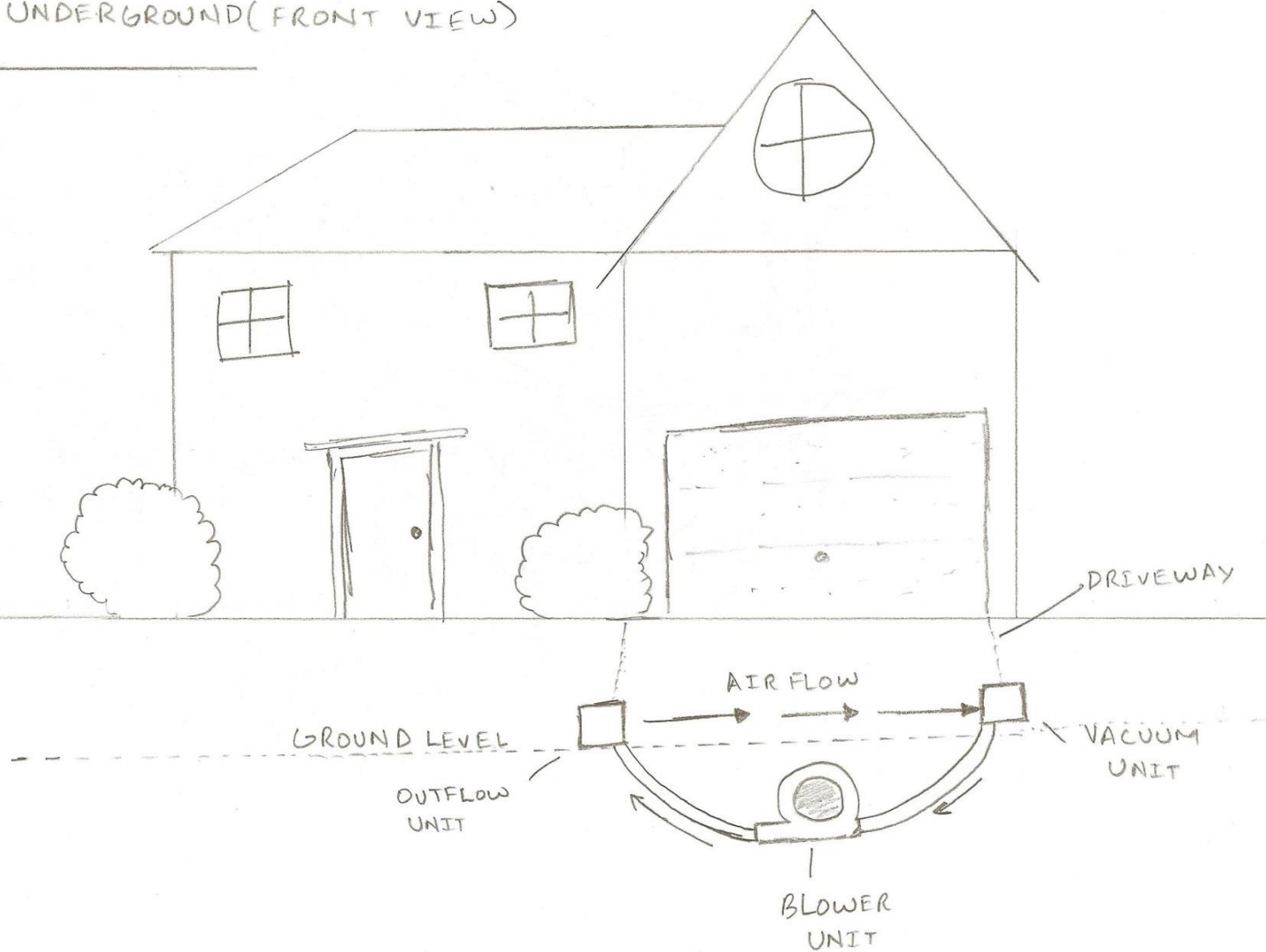
DESIGN 4



CYCLICAL FLOW UNIT

DESIGN 4

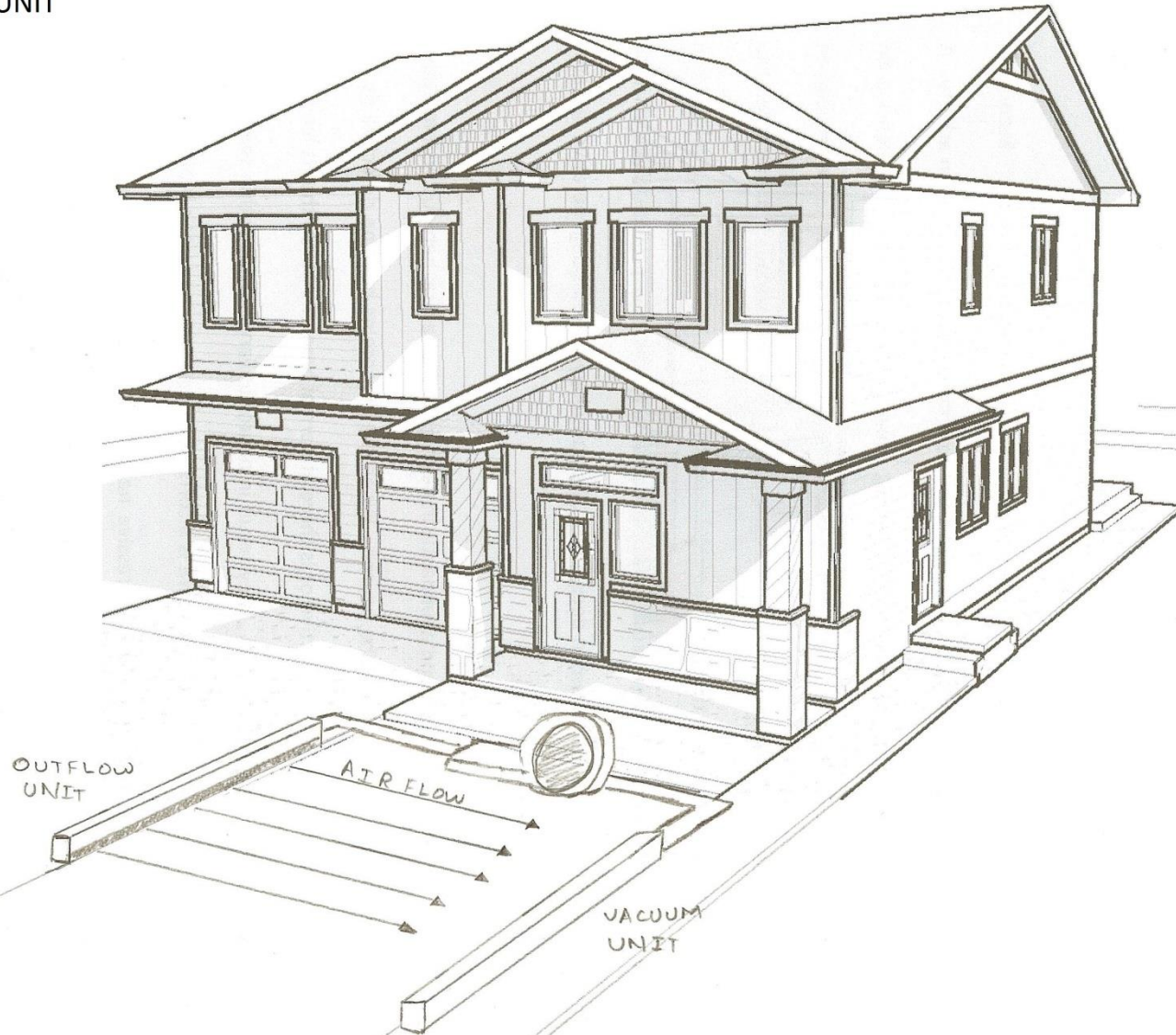
W/ BLOWER UNDERGROUND (FRONT VIEW)



4.5 Design 5 – Cyclical Flow Above Ground Unit

DESIGN 5

CYCLICAL FLOW UNIT
GROUND UNIT



Brush/Shovel Instead of Air:

Other than the possible designs shown above, I had thought of another one which utilizes a brush/plow that pushes the snow to one side (detailed in Designs 6 & 7 below). Once the snow reaches the other side, the brushes will push it onto the panel, and the brushes will return to their original position. This panel will turn about an axis and will be equipped with a mechanism that allows it to launch the snow into an area away from the driveway. There is no air flow involved. However, the design criteria/ performance specifications from before still apply.

Note: In Design 7, the exact mechanism for the snow flipping panel/flap wasn't detailed in the drawing since I don't know much about that mechanism yet. I think it could be simple as an electric motor turning a gear on the panel's turning axis. (The turning motion will be an impulse force, which will be able to launch the snow.)

Other mechanisms that might work: Spring loaded release, linear escapement mechanism, air bag underneath the turning panel/flap.

DESIGN 6

4.6 Design 6 – Brush/Shovel Blade With Heated Snow Gutter



RACK
&
PINION

BRUSH

BRUSH →

SNOW GUTTER (HEATED)

UNDGRND
DRAIN

DESIGN 7

4.7 Design 7 – Brush/Shovel Blade With Snow Launching Panel



RACK &
PINION

BRUSH

AXIS

AXIS

PANEL (ROTATES ABOUT AXIS)

<u>Design Decision Matrix</u> (Norton, 2006)	Cost for Parts and Mfg.	Cost for Installation	Ease of Disassembling and Storage for Summer	Energy Consumption	Average	Rank
Design 1 (Axial Fans- Ground)	3	1	1	2	1.75	3
Design 2 (Centrifugal Blower- Ground)	2	1	1.5	1.5	1.50	2
Design 3 (Axial Fans on Tent)	4.5	1.5	2.5	1	2.38	6
Design 4 (Cyclical Flow- Centrifugal -Underground)	5	5	1	1.5	3.13	7
Design 5 (Cyclical Flow- Centrifugal -Above Ground)	4	1.5	1.5	1.5	2.13	5
Design 6 (Brush W/ Heated Snow Drain)	2	3	2	0.25	1.81	4
Design 7 (Brush W/ Snow Launching Panel/Flap)	2.5	1	1	0.5	1.25	1

4.8 Design Decision Matrix Results and Designing Actuators for Design 7 Concept

In this matrix, the winning design is the one with the lowest score. That happened to be Design 7, the “Brush/ Shovel Blade with Snow Launching Panel”. In second place was Design 2 the “Blower with Centrifugal Fan”.

As mentioned earlier, the Design Decision Matrix was one of the initial filtering steps that was used to narrow down to a specific design. These design specifications were mostly qualitative in nature such as cost, storage and installation difficulty. Those parameters could not hold up to empirical scrutiny, which is why in the following sections, new designs for actuators for Design 7 will be presented. This will be done while simultaneously performing force analyses on them. It was decided that the laminar air flow concept would not be furthered as the fans were very expensive and testing would require multiple ones since effective use involved blowing air into a wide open space and not some closed system.

The actuator designs in the following sections improve upon the concepts introduced in Designs 6 and 7. The main aim for the force analysis was to be able to find where maximum forces occurred in the actuators and what their magnitudes would be. This is because the maximum force within the actuators directly correlates with the parameters for support forces, installation difficulty and structural weaknesses. And comments could be made about those parameters empirically, based on the idea that the lower the max force within the system is, the lesser the values for those parameters are going to be. This, along with an energy analysis was done for each design.

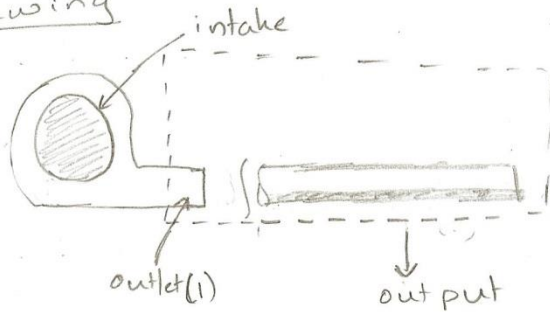
4.8.1 Energy Calculations for Design 2

Note: Output opening Dimensions: 5.48m X 0.03m

Energy Balance for: Design 2 (Centrifugal Blower)

Blower: MB-1665-B (oriental motor)

Drawing



Assumptions

- 1) steady state
- 2) Temp. Air = 0°C
- 3) $\rho_{\text{air}} = 1.2754 \text{ kg/m}^3$
- 4) $\Delta z = 0$
- 5) Neglect static friction

$$0 = \dot{Q}_{\text{in}} + \dot{W}_{\text{in}} + \sum_{\text{inlets}} \dot{m}_1 \left[h_1 + \frac{V_1^2}{2} + gz \right] - \sum \dot{m}_2 \left[h_2 + \frac{V_2^2}{2} + gz \right]$$

Power = 260 watts, CFM = 282 $\text{ft}^3/\text{min} \Rightarrow$ Mass flow rate = $\rho \cdot \text{CFM} = 0.170 \frac{\text{kg}}{\text{s}}$

$h = -197.92 \text{ kJ/kg @ } 0^\circ\text{C}$

$$\dot{m} = \rho \cdot A \cdot V \Rightarrow V_1 = \frac{\dot{m}}{\rho \cdot A_1} \Rightarrow \frac{0.170 \text{ kg/s}}{(1.2754 \frac{\text{kg}}{\text{m}^3}) \cdot (7.068 \times 10^{-3} \text{ m}^2)} = 18.85 \text{ m/s} //$$

$$V_2 = \frac{\dot{m}}{\rho A_2} \Rightarrow \frac{0.170 \text{ kg/s}}{(1.2754 \frac{\text{kg}}{\text{m}^3}) \cdot (0.164 \text{ m}^2)} = 0.81 \text{ m/s} //$$

$$\Rightarrow 0 = \dot{Q}_{\text{in}} + 260 \text{ J/s} + 0.170 \frac{\text{kg}}{\text{s}} \left[273.4 \frac{\text{kJ}}{\text{kg}} + \frac{18.85^2}{2} \text{ m/s} + 0 \right] - 0.170 \frac{\text{kg}}{\text{s}} \left[273.4 \frac{\text{kJ}}{\text{kg}} + \frac{0.81^2}{2} \text{ m/s} + 0 \right]$$

$$\Rightarrow 0 = \dot{Q}_{\text{in}} + 260 \text{ J/s} + \left[46.48 \frac{\text{kJ}}{\text{s}} + 0.030202 \frac{\text{kJ}}{\text{s}} - 46.48 \frac{\text{kJ}}{\text{s}} - 5.57 \times 10^{-5} \frac{\text{kJ}}{\text{s}} \right]$$

$$-\dot{Q}_{\text{in}} = 260 \text{ J/s} + 30.20 \text{ J/s} - 0.0557 \Rightarrow -\dot{Q}_{\text{in}} = 290.14 \text{ watts}$$

Efficiency

$$\eta = \frac{260 - 30.14}{260} = 88\%$$

Efficiency of Plow truck: 30%

Efficiency of snow blower (gas powered): 25% - 30%

Reynolds Number - Air at 0°C

$$Re = \frac{\rho V L}{\mu} \Rightarrow \frac{(1.2754)(.81)(5.48)}{(1.787 \times 10^{-6})} = 3,168,016$$

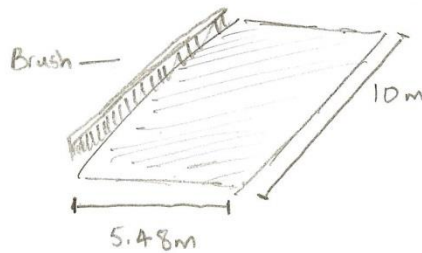
$Re > 4000$, thus it's turbulent flow.

4.8.2 Energy Calculations for Brush Device

ENERGY REQ'S FOR OPERATION OF BRUSH DEVICE

▶ Electric motor: 0.5 HP (Garage Door Opener Motor)

▶ Driveway Dimensions: 5.486 m X 10 m
(width) (Length)



▶ Approximate time required for cleaner to go from one side of driveway to other: 60secs.

▶ Time interval between above mentioned cycle: 15mins.

▶ Total running time over course of 6 hour night: 1440 seconds
or

▶ Total energy costs (@ 13¢ per kWh): 0.4 hours

0.5 HP → 373 Watts
motor

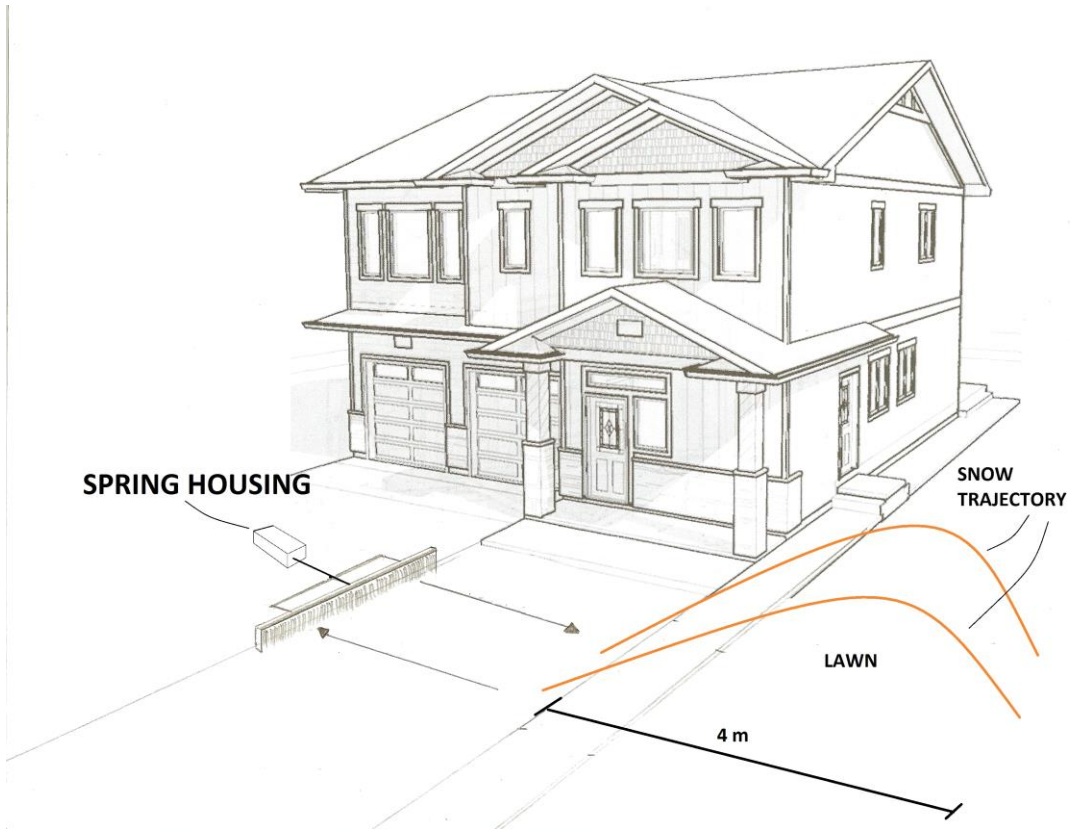
$$373 \text{ W} * 0.4 \text{ hours} = \boxed{0.1492 \text{ kWh}}$$

$$0.1492 \text{ kWh} * \frac{13¢}{\text{kWh}} =$$

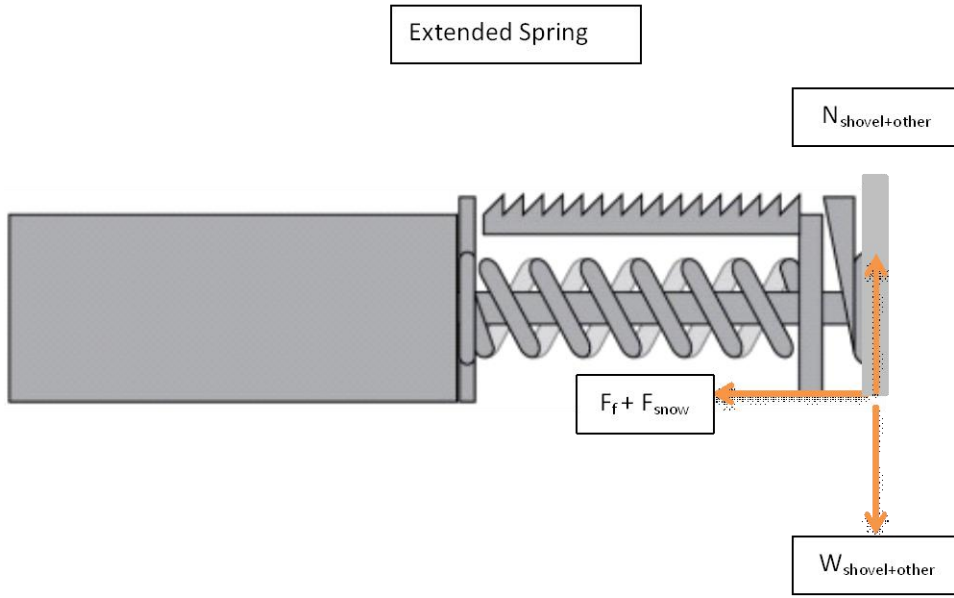
2 ¢
overnight use (6 hr)

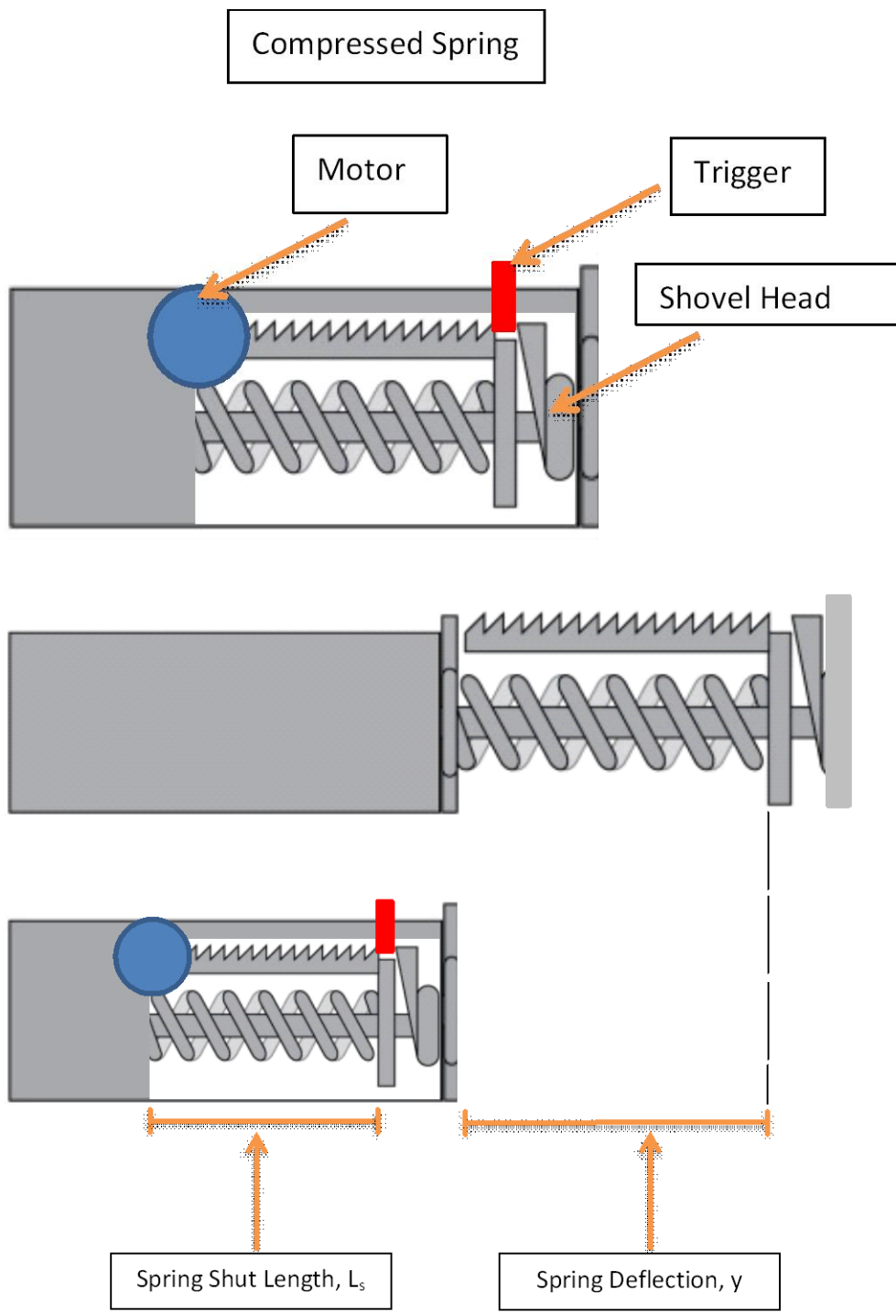
Note: This estimate does not include operating costs for snow launching panel/flap.

4.9 Design 7.1 – Spring Launcher Actuator



Free Body Diagram





Snow Weight

$d_{\text{driveway}} := 4.57\text{m}$ This is the horizontal distance (width of driveway)

$\rho_{\text{snow}} := 800 \frac{\text{kg}}{\text{m}^3}$ For slushy snow

$h_{\text{snow}} := 2\text{cm}$

$\text{Width}_{\text{shovel}} := 0.6\text{m}$

$\text{Area}_{\text{clear}} := \text{Width}_{\text{shovel}} \cdot d_{\text{driveway}} = 2.742\text{m}^2$

$V_{\text{snow}} := (\text{Area}_{\text{clear}} \cdot h_{\text{snow}}) = 0.055\text{m}^3$

$M_{\text{snow}} := \rho_{\text{snow}} \cdot V_{\text{snow}} = 43.872\text{kg}$

$W_{\text{snow}} := M_{\text{snow}} \cdot g = 430.237\text{N}$

Shovel Weight

Material : Alloy Steel, mass calculated by SolidWorks

$M_{\text{shovel}} := 9.67\text{kg}$

$W_{\text{shovel}} := 9.67\text{kg} \cdot g = 94.83\text{N}$

Other Weights

$M_{\text{other}} := 2\text{kg}$

$W_{\text{other}} := M_{\text{other}} \cdot g = 19.613\text{N}$

Total Normal Force

$F_{\text{normal}} := W_{\text{shovel}} + W_{\text{other}} = 114.444\text{N}$

Friction between Shovel and Ground

$N_s := W_{\text{shovel}} + W_{\text{other}} = 114.444\text{N}$

Kinetic friction between steel and concrete $\mu_s := 0.75$

Friction factor obtained from $F_{\text{sg}} := \mu_s \cdot N_s = 85.833\text{N}$
(http://www.academia.edu/5307385/WTC2005-63579_FRICTION_BETWEEN_STEEL_AND_ASPHALT_WITHOUT_GOUGING_UNDER_REPRESENTATIVE_IMPACT_PRESSURES)

Work done to overcome shovel friction

$W_{\text{sg}} := F_{\text{sg}} \cdot d_{\text{driveway}} = 392.255\text{J}$

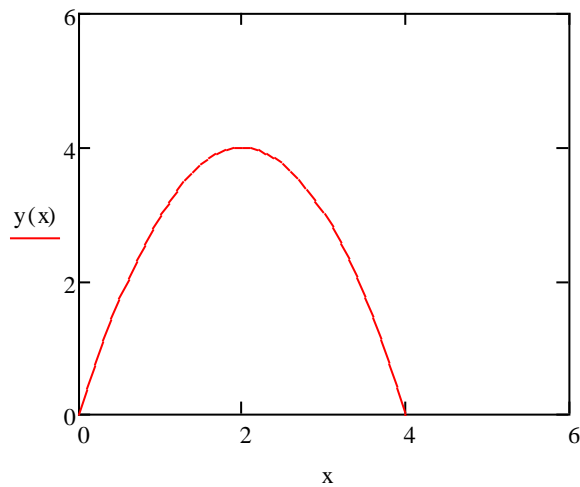
Energy

Assuming that snow travels in a parabolic form

Let us take this equation

$$x := 0, 0.1..10$$

$$y(x) := 4x - x^2$$



Assuming the above graph is the trajectory for the snow.

Launch Angle

Height of vertex in meters $S := 4\text{m}$

Range in meters $r := 4\text{m}$

Launch Angle $\theta_{\text{launch}} := \text{atan}\left(\frac{4S}{r}\right) = 75.964\text{deg}$

Launch Velocity

$$v_f := \sqrt{\frac{r \cdot g}{\sin(2\theta_{\text{launch}})}} = 9.13 \frac{\text{m}}{\text{s}}$$

Energy for Launching Snow in Air

$$\Sigma M := M_{\text{snow}} + M_{\text{shovel}} + M_{\text{other}} = 55.542\text{kg}$$

$$\boxed{KE_{\text{launch}} := \left(\frac{1}{2}\right) \cdot \Sigma M \cdot v_f^2 = 2.315 \times 10^3 \text{ J}}$$

Total Energy for One Launch

Total Energy = Energy for Launching snow in Air + Work done to overcome frictional energy

$$\boxed{\Sigma E := KE_{\text{launch}} + W_{\text{sg}} = 2.707 \times 10^3 \text{ J}}$$

This total energy should equal to the PE stored in the spring

Choosing Electric Motor

$$P = \frac{\tau \cdot (2\pi \cdot n)}{60s} \quad \text{where } \tau \text{ is torque and } n \text{ is the rpm}$$

From before we have ΣE $P := \frac{\Sigma E}{30s} = 90.238\text{W}$ 30 seconds is the total time we are allotting the motor to fully compress the spring

if we assumed that the shaft had an rpm of 60 $n := 60$

$$P = \frac{\tau \cdot (2\pi \cdot n)}{60s} \text{ solve, } \tau \rightarrow 14.36187422608126518\text{N}\cdot\text{m} = 14.362\text{N}\cdot\text{m}$$

Torque of Motor has to be $\boxed{\tau = 14.4\text{N}\cdot\text{m}}$

Spring Specifications

For these sections, all information and equations are obtained from Chapter 13 (Spring Design)

of Norton Machine Design.

We know that $W=F \cdot d$, therefore we obtain, F from the total energy

$$\Sigma F := \frac{\Sigma E}{d_{\text{driveway}}} = 592.374\text{N}$$

$$F_{\text{spring}} = k \cdot y \quad \text{where } k \text{ is the spring constant, and } y \text{ is the deflection}$$

$$F_{\text{spring}} := \Sigma F = 592.374\text{N}$$

$$y := d_{\text{driveway}} \quad \text{spring deflection, } y \text{ is equal to length of the driveway, since that is how far the spring need to expand to clear snow off driveway}$$

$$\text{Spring constant} \quad k := \frac{F_{\text{spring}}}{y} = 129.622 \frac{\text{kg}}{\text{s}^2}$$

Diameter of Coils

- Preferred range of C is from 4 to 12, I will choose 8 (Norton, Spring Design)

$$C = \frac{D}{d}$$

$$C := 8 \quad d := 0.004\text{r} - \text{Assuming } d = 4\text{mm}$$

$$\text{Therefore, coil diameter } D \text{ equals} \quad [D := C \cdot d = 0.032\text{m}]$$

Determining Spring Material

The spring material that we are analyzing is 228 ASTM/SAE 1085, Music Wire, because it is the toughest, most widely used material for small coil springs. It has the highest tensile and fatigue strength of all spring wire. (Norton Machine Design)

Length of Spring

$$y = \frac{8 \cdot F \cdot D^3 \cdot N_a}{d^4 \cdot G}$$

F - force on the spring

D - coil diameter

N.t - number of coils

$$F := F_{\text{spring}} = 592.374\text{N} \quad D = 0.032\text{m} \quad d := 0.004\text{r} \quad G := 80 \times 10^9 \frac{\text{N}}{\text{m}^2}$$

d - wire diameter

G - shear modulus

$$y = \frac{8 \cdot F \cdot D^3 \cdot N_t}{d^4 \cdot G} \text{ solve, } N_t \rightarrow 602.71248569289890984602.712$$

$$N_t := 391$$

For squared ground ends

$$\text{Number of active coils } N_a := N_t - 2 = 389$$

Shut Length of Spring

$$L_s := N_a \cdot d = 1.556\text{m}$$

Cost of Spring

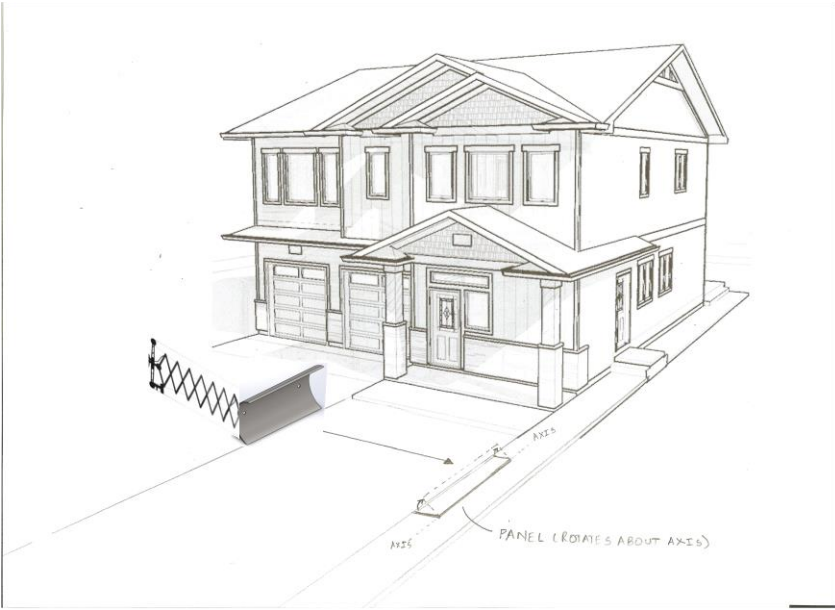
Total Cost: \$6.43 based on <http://www.acxesspring.com/spring-calculator.html>

Max Force within System

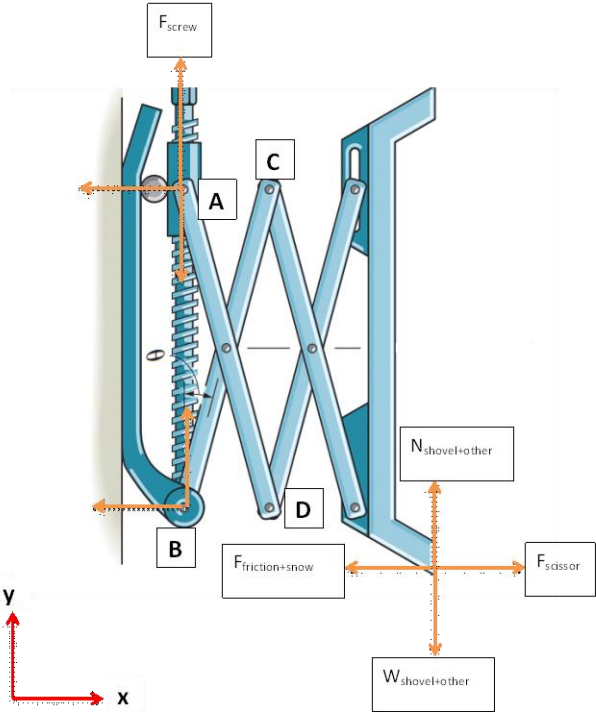
$$F_{\text{max}} := \Sigma F = 592.374\text{N}$$

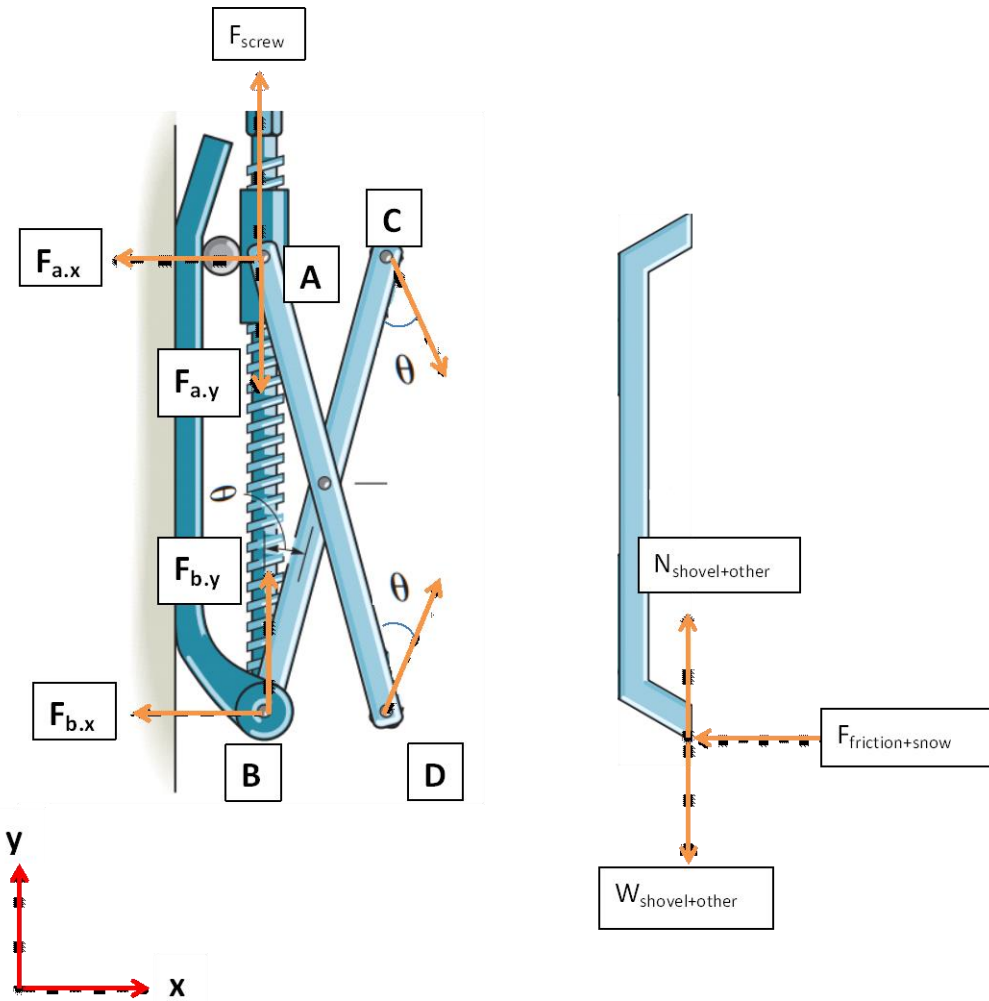
This Force occurs in the Spring when it is fully loaded.

4.10 Design 7.2 – Scissor Arm Actuator



Free Body Diagram





In the Above FBD's please assume that there are roller balls at the base of points B and D.

This is to allow screw jack to act as if were in the upright position.

Snow Weight

$$d_{\text{driveway}} := 4.57\text{m}$$

$$\rho_{\text{snow}} := 800 \frac{\text{kg}}{\text{m}^3}$$

$$h_{\text{snow}} := 2\text{cm}$$

$$\text{Area}_{\text{snow}} := 0.6\text{m} \cdot 1\text{m} = 0.6\text{m}^2$$

$$V_s := (\text{Area}_{\text{snow}} \cdot h_{\text{snow}}) = 0.012\text{m}^3$$

$$M_{\text{snow}} := \rho_{\text{snow}} \cdot V_s = 9.6\text{kg}$$

$$W_{\text{snow}} := M_{\text{snow}} \cdot g = 94.144\text{N}$$

Shovel Weight

Material : Alloy Steel, mass calculated by SolidWorks

$$M_{\text{shovel}} := 9.67\text{kg}$$

$$W_{\text{shovel}} := 9.67\text{kg} \cdot g = 94.83\text{N}$$

Other Weights

$$M_{\text{other}} := 2\text{kg}$$

$$W_{\text{other}} := M_{\text{other}} \cdot g = 19.613\text{N}$$

Friction between Shovel and Ground

$$N_s := W_{\text{shovel}} + W_{\text{other}} = 114.444\text{N}$$

Kinetic friction between steel and concrete $\mu_s := 0.75$

Friction factor obtained from $F_{\text{sg}} := \mu_s \cdot N_s = 85.833\text{N}$

(http://www.academia.edu/5307385/WTC2005-63579_FRICTION_BETWEEN_STEEL_AND_ASPHALT_WITHOUT_GOUGING_UNDER_REPRESENTATIVE_IMPACT_PRESSURES)

Work done to overcome shovel friction

$$W_{\text{sg}} := F_{\text{sg}} \cdot d_{\text{driveway}} = 392.255\text{J}$$

Friction Between Snow and Ground

$$\mu_s := 0.5$$

$$F_s := \mu_s \cdot W_{\text{snow}} = 47.072\text{N}$$

$$W_s := F_s \cdot d_{\text{driveway}} = 215.119\text{J}$$

Determining Screw Friction

Where N is the weight of the screw

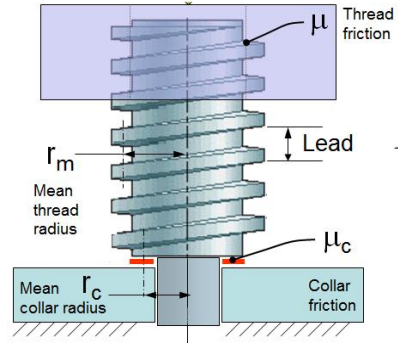
$$N := 3\text{kg} \cdot g = 29.42\text{N}$$

Where μ and μ_c is the coefficient of friction

$$\mu := 0.1 \quad \mu_c := 0.15$$

in the major and collar diameter

$$F_{\text{screwfric}} := \mu \cdot N + \mu_c \cdot N = 7.943\text{N}$$



Determining Components of Force at Point D

$$\Sigma F_y = 0 \quad F_{\text{screwfric}} + F_D \cdot \cos(\theta) = 0$$

$$\Sigma F_x = 0 \quad -F_{sg} - F_{\text{snow}} + F_D \cdot \sin(\theta) = 0$$

On calculation we get $\theta := 87\text{deg}$

$$F_D := 202.3\text{N}$$

$$F_{Dx} := F_D \cdot \sin(\theta) = 5.943 \times 10^3 \text{ N}$$

$$F_{Dy} := F_D \cdot \cos(\theta) = 311.486\text{N}$$

Determine Torque Required to Start the Scissors

Assume following dimensions

single square thread screw

$d := 22\text{mm}$ major diameter

$d_c := 14\text{mm}$ minor diameter

$p := 8\text{mm}$ pitch, distance between center of threads

$f_c := 0.12$ friction of major diameter

$f := 0.15$ friction of minor diameter

$d_m := d - \left(\frac{p}{2}\right) = 0.018\text{m}$ mean diameter

Instead of W put in F_{screw}

$$\text{Torque } \tau := \left(\frac{F_{\text{screwfric}} \cdot d_m}{2} \right) \cdot \left(\frac{f \cdot \pi \cdot d_m + p}{\pi \cdot d_m - f \cdot p} \right) + \left(\frac{F_{\text{screwfric}} \cdot f_c \cdot d_c}{2} \right) = 9.504 \times 10^{-4} \cdot \text{N} \cdot \text{m}$$

Power Required for Overcoming Friction

$$\text{Fric}_{\text{tot}} := F_{\text{sg}} + F_{\text{screwfric}} + F_s = 140.848\text{N}$$

$$\text{Work } W := \text{Fric}_{\text{tot}} \cdot d_{\text{driveway}} = 643.675\text{J}$$

$$\text{Power } \left[P_{\text{fric}} := \frac{W}{30\text{s}} = 21.456\text{W} \right]$$

Obtaining Power Rating from Torque Equation

$n := 60$ where τ is torque and n is the rpm

$$\left[P_{\text{torque}} := \frac{\tau \cdot (2\pi \cdot n)}{60\text{s}} = 0.176\text{W} \right]$$

Total Power Rating for Motor

$$\left[P_{\text{tot}} := P_{\text{fric}} + P_{\text{torque}} = 21.632\text{W} \right]$$

Stress Within Screw

For this Statically Indeterminate System, we will use Principle of Virtual Work

Assuming that each Linkage has a length, L

$$L := 0.15r \quad \text{based on height of Shovel Head}$$

$$\theta := .1745 \quad \text{in radians (10 degrees)}$$

$$x := 2 \cdot L \cdot \sin(\theta)$$

$$y := L \cdot \cos(\theta)$$

Assuming:

1) Arbitrary infinitesimal change in the position of the Shovel Head, δ .s

$$\delta_x = 2 \cdot L \cdot \cos(\theta) \cdot \delta\theta$$

2) Change in Energy of System = 0

$$\delta_y = -L \cdot \sin(\theta) \cdot \delta\theta$$

$$\delta U := 0 \quad \text{Therefore}$$

$$\delta U = F_{\text{tot}} \cdot \delta_x - F \cdot \delta_y$$

$$\delta U = -W_{\text{tot}}(2 \cdot L \cdot \cos(\theta) \cdot \delta\theta) - F(-L \cdot \sin(\theta) \cdot \delta\theta)$$

$$F_{\text{screw}} := 2 \cot(\theta) \cdot W = 7.301 \text{m} \cdot \text{kN}$$

$$\text{Area}_{\text{screw}} := \left(\frac{1}{4}\right) \cdot \left(\pi \cdot d_c^2\right) = 1.539 \times 10^{-4} \text{m}^2$$

Stress within Screw:

$$\sigma := \frac{F_{\text{screw}}}{\text{Area}_{\text{screw}}} = 47.429 \text{m} \cdot \text{MPa}$$

Taking material as Cast Iron we see the Young's Modulus is 10^9 Pa or 1 GPa

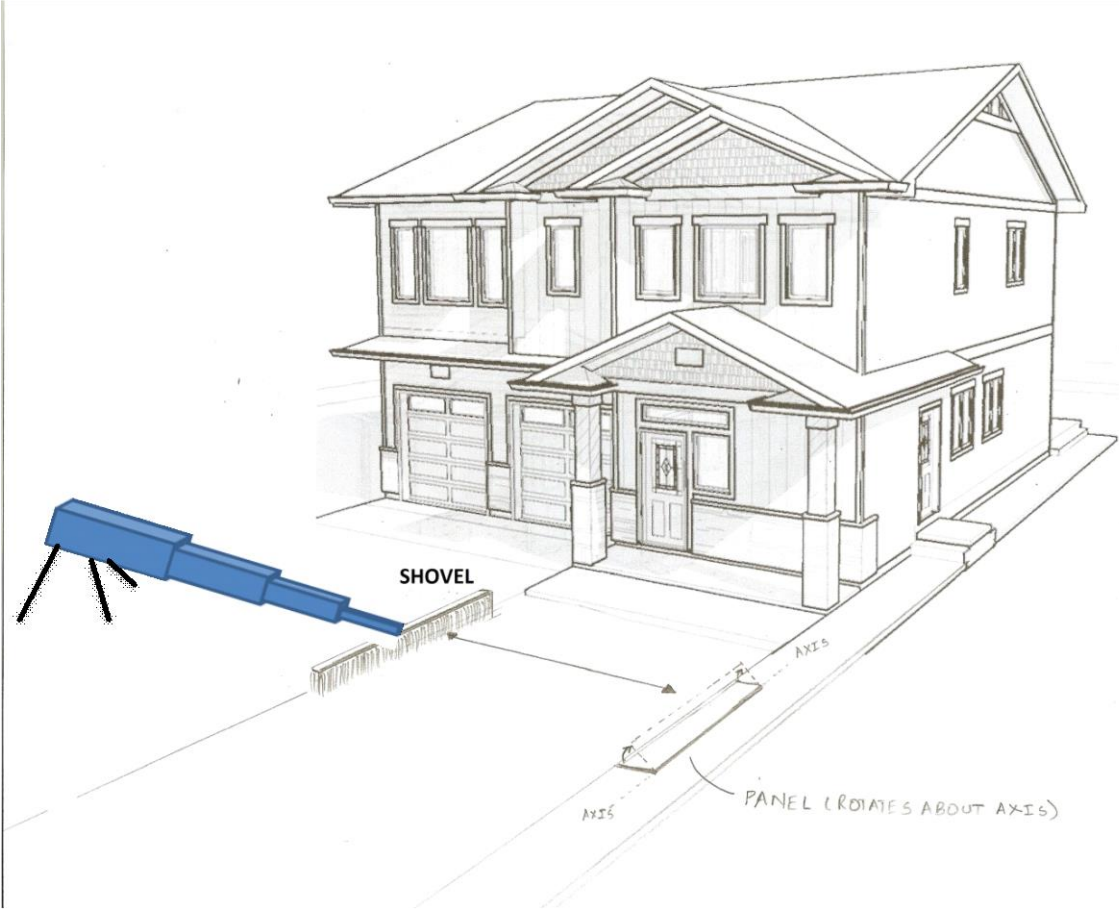
which is well over the max stress for the scissor device

Max Force in System

$$F_{\max} := F_{Dx} = 5.943 \times 10^3 \text{ N}$$

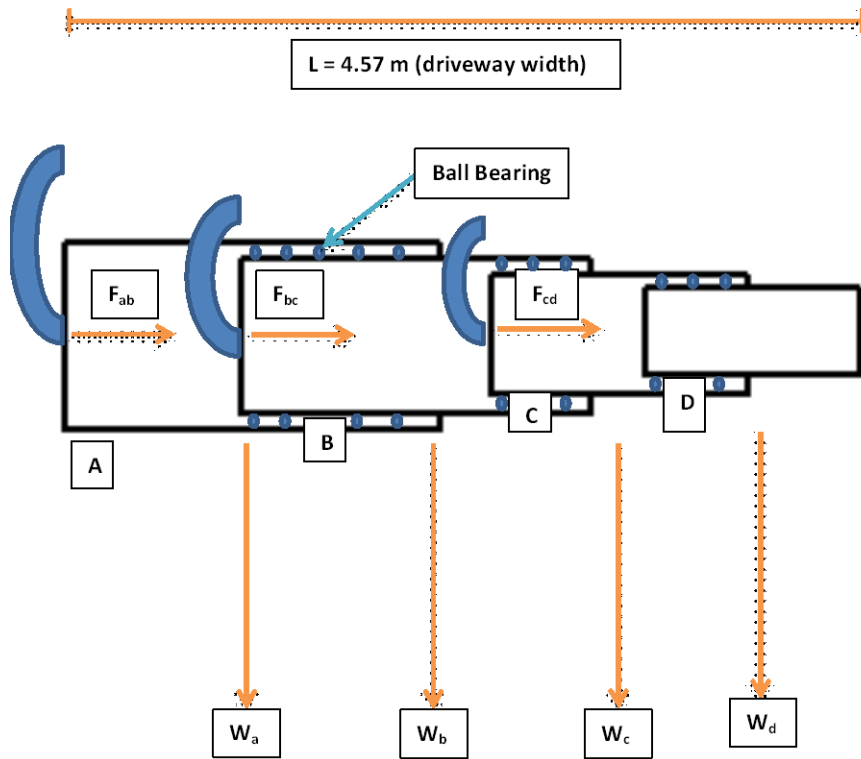
The Max Force occurs at F.D

4.11 Design 7.4 - Telescopic Extender Arm Actuator



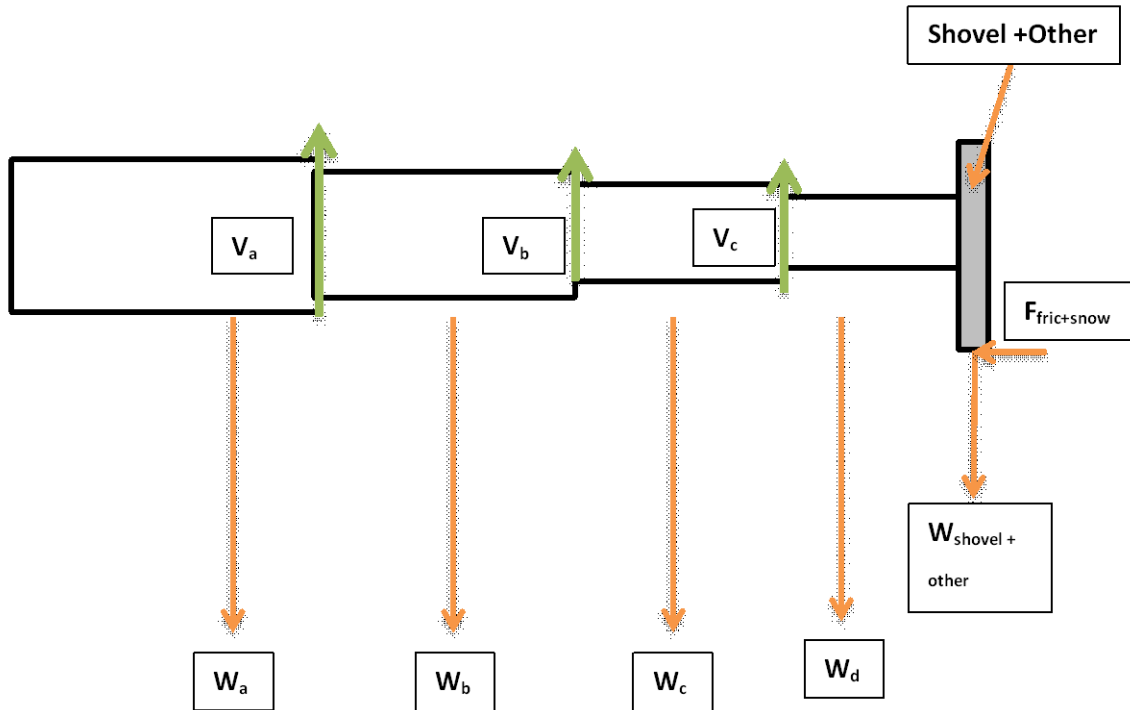
In this design the telescopic arm will be using air as the "hydraulic fluid"

Free Body Diagram



- There are four compartments to the extending arm
- Each of those is a separate cylinder/piston
- The blue tubes carry the pressurized air into the cylinders

Max Shear Locations



Choosing a Material for the Piston Cylinders

I will be using the Chromium- Nickel Stainless Steel (ASTM A240), because it is used in heavy duty hydraulic cylinder construction and offers superior corrosion resistance for greater durability in harsh environments as given at this website:

http://www.aksteel.com/pdf/markets_products/stainless/austenitic/316_316l_data_sheet.pdf

$$\rho := 7.700 \frac{\text{kg}}{\text{m}^3}$$

Dimensions of the Arm

When extended the length of the arm has to equal the length of the driveway, 4.57 m

$$L_e := 4.57\text{m}$$

Based on the FBD arrangement, the lengths and areas of the cylinders are as follows for a 4.57 m driveway

Although the following may look confusing, it is just playing around with ratios to find the right dimensions

$$\begin{aligned} L_a &:= 1.492\text{m} & A_a &:= \left(\frac{L_a}{3}\right)^2 = 0.247\text{m}^2 \\ L_b &:= 1.260\text{m} & A_b &:= \left(\frac{L_b}{3}\right)^2 = 0.176\text{m}^2 \\ L_c &:= 1.061\text{m} & A_c &:= \left(\frac{L_c}{3}\right)^2 = 0.125\text{m}^2 \\ L_d &:= 0.756\text{m} & A_d &:= \left(\frac{L_d}{3}\right)^2 = 0.064\text{m}^2 \end{aligned}$$

Calculating Volume of cylinders, given that the walls have a 1.5 cm thickness

$$V_a := (3\text{cm} \cdot A_a + 2\text{cm} L_a^2) - (A_b \cdot 1.5\text{cm}) = 0.049\text{m}^3$$

$$V_b := (3\text{cm} \cdot A_b + 2\text{cm} L_b^2) - (A_c \cdot 1.5\text{cm}) = 0.035\text{m}^3$$

$$V_c := (3\text{cm} \cdot A_c + 2\text{cm} L_c^2) - (A_d \cdot 1.5\text{cm}) = 0.025\text{m}^3$$

$$V_d := (3\text{cm} \cdot A_d + 2\text{cm} L_d^2) = 0.013\text{m}^3$$

Weight of Each Cylinder

$$W_a := V_a \cdot \rho \cdot g = 3.722\text{N} \quad W_c := V_c \cdot \rho \cdot g = 1.912\text{N}$$

$$W_b := V_b \cdot \rho \cdot g = 2.656\text{N} \quad W_d := V_d \cdot \rho \cdot g = 1.007\text{N}$$

Choosing Bearing Type

- We will look at the max shear the cylinder has to withstand in order to determine the right type of bearing for this application. We are choosing Cylinder A as it supports the weight of all the rest of the Telescopic Arm.

- In this we will assume that the moment on the arm is 0

Snow Weight

$d_{\text{driveway}} := 4.57\text{m}$ This is the horizontal distance (width of driveway)

$\rho_{\text{snow}} := 800 \frac{\text{kg}}{\text{m}^3}$ For slushy snow

$h_{\text{snow}} := 2\text{cm}$

$\text{Width}_{\text{shovel}} := 0.6\text{m}$

$\text{Area}_{\text{clear}} := \text{Width}_{\text{shovel}} \cdot d_{\text{driveway}} = 2.742\text{m}^2$

$V_{\text{snow}} := (\text{Area}_{\text{clear}} \cdot h_{\text{snow}}) = 0.055\text{m}^3$

$M_{\text{snow}} := \rho_{\text{snow}} \cdot V_{\text{snow}} = 43.872\text{kg}$

$W_{\text{snow}} := M_{\text{snow}} \cdot g = 430.237\text{N}$

Shovel

Material : Alloy Steel, mass calculated by SolidWorks

Other Weights

$M_{\text{shovel}} := 9.67\text{kg}$

$M_{\text{other}} := 2\text{kg}$

$W_{\text{shovel}} := 9.67\text{kg} \cdot g = 94.83\text{N}$

$W_{\text{other}} := M_{\text{other}} \cdot g = 19.613\text{N}$

Max Shear Force

$$V_{\text{max}} := W_b + W_c + W_d + W_{\text{shovel}} + W_{\text{other}} = 120.018\text{N}$$

- Since the telescopic arm is a square shape, a normal roller bearing wouldn't fit this application

- So we will be using ball transfer (image below)

- The make is SKF Type 3000, which can bear loads of up to 245 N

- <http://www.skf.com/binary/30-97863/Ball-Transfer-units.pdf>



Bearing Chosen: SKF Ball Transfer, Type 3000, max load of 245 N

Number of Ball Bearings to be Used

Cylinder A will need to support V_{max} , which is $V_{max} = 120.018N$

- And since the rest of the cylinders will be supporting less than we don't need to calculate the values for those
- It would seem one of the bearings would be more than enough for supporting each cylinder, but since the next cylinder inside it wouldn't be balanced, it is necessary to have 4 on the top and bottom and 2 on either side
- We would need a total of 36 ball transfers

Total Number of Ball Transfers: 36

Price For Ball Transfers

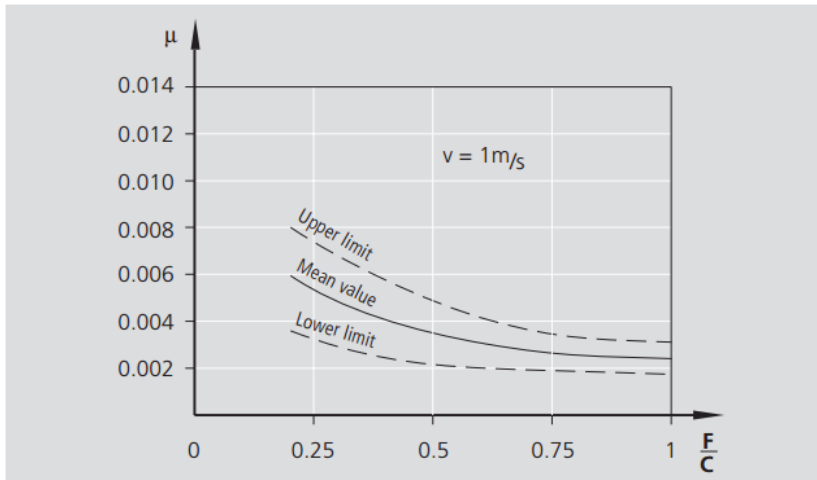
Using the price of a similar SKF Ball transfer @ \$41.46 per piece we calculated the price to be:

$$P_{ball} = \$1,493$$

<http://www.mscdirect.com/product/details/06377493>

Bearing Friction

L = Nominal life	(rotations)
C = Load capacity	(N)
F = Load	(N)



<http://www.irusa.com.br/catalogos/Bosch%20-%20Rexroth/Esferas%20Transferidoras.pdf>

Assuming the highest coefficient of friction of $\mu := 0.008$

Normal force at Cylinder A

$$\text{Max Normal at A} \quad N_a := V_{\max}$$

$$F_a := \mu \cdot N_a = 0.96 \text{ N}$$

Normal force at Cylinder B

$$\text{Max Normal at B} \quad N_b := W_c + W_d + W_{\text{shovel}} + W_{\text{other}} = 117.362 \text{ N}$$

$$F_b := \mu \cdot N_b = 0.939 \text{ N}$$

Normal force at Cylinder C

$$N_c := W_d + W_{\text{shovel}} + W_{\text{other}} = 115.45 \text{ IN}$$

$$F_c := \mu \cdot N_c = 0.924 \text{ N}$$

Friction between Shovel and Ground

$$N_s := W_{\text{shovel}} + W_{\text{other}} = 114.444 \text{ N}$$

Kinetic Friction between steel and concrete $\mu_s := 0.75$

Friction factor obtained from $F_{sg} := \mu_s \cdot N_s = 85.833 \text{ N}$
(http://www.academia.edu/5307385/WTC2005-63579_FRICTION_BETWEEN_STEEL_AND_ASPHALT_WITHOUT_GOUGING_UNDER_REPRESENTATIVE_IMPACT_PRESSURES)

Work done to overcome shovel friction $W_{sg} := F_{sg} \cdot d_{\text{driveway}} = 392.255 \text{ J}$

Friction Between Snow and Ground

$$\mu_s := 0.5$$

$$F_s := \mu_s \cdot W_{\text{snow}} = 215.119 \text{ N}$$

$$W_s := F_s \cdot d_{\text{driveway}} = 983.092 \text{ J}$$

Total Friction Force

$$F_{\text{tot}} := F_a + F_b + F_c + F_{sg} + F_s = 303.774 \text{ N}$$

Air Pressure Needed for 1 Sweep

The air Pressure needed at each cylinder to be able to overcome Friction

$$A_{\text{tot}} := A_b + A_c + A_d = 0.365 \text{ m}^2$$

$$P_{\text{tot}} := \frac{F_{\text{tot}}}{A_{\text{tot}}} = 832.294 \text{ Pa}$$

The Max Force is present throughout the arm when it is fully extended.

Work done by Air on Cylinders

Volume for expansion $V := (A_a \cdot L_a) + (A_b \cdot L_b) + (A_c \cdot L_c) = 0.724 \text{m}^3$

$$W = -P_{\text{tot}} \cdot V \cdot \left(\int_0^V \frac{1}{V} dV \right) \quad \text{we have} \quad \boxed{W := -P_{\text{tot}} \cdot V \cdot \ln(0.724) = 194.613 \text{J}}$$

Power Rating for Air Compressor

$$P := \frac{W}{10\text{s}} = 19.461 \text{W}$$

A commercially available air compressor of 150 W is sufficient for this application.

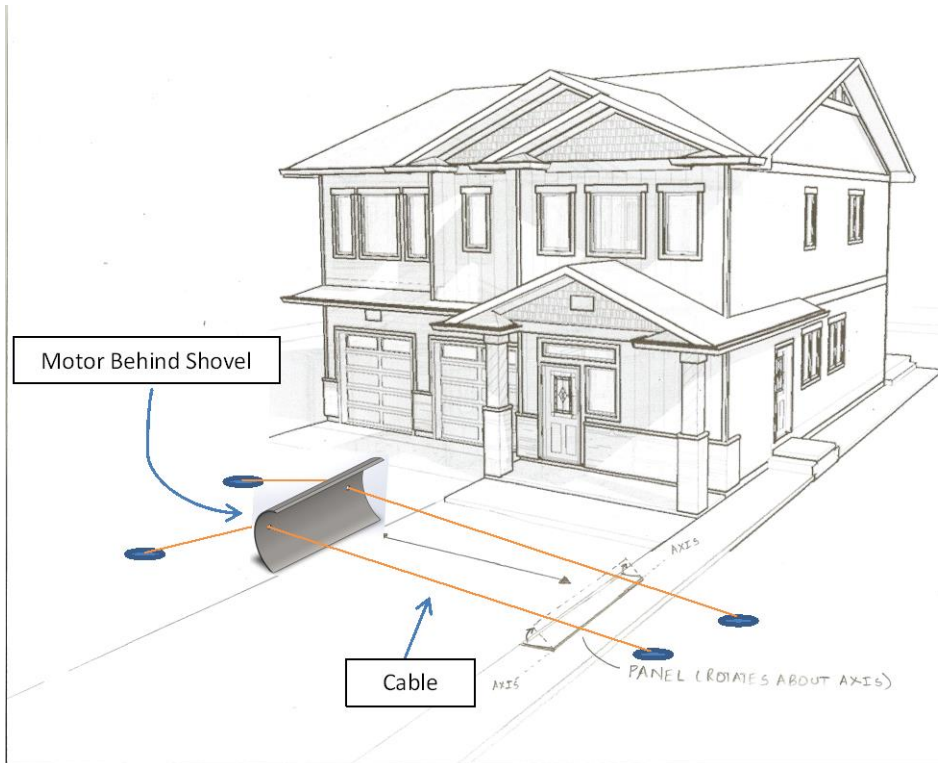
Price will be about \$50- \$150

Total Price with ball bearings might cost about \$1600.00

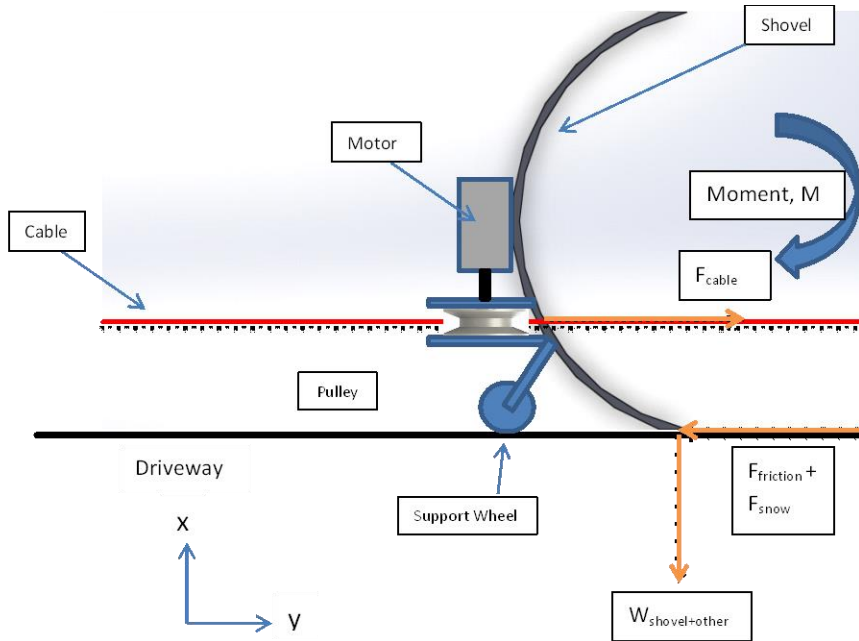
Max Force in System

$$\boxed{F_{\text{max}} := F_{\text{tot}} = 303.774 \text{N}}$$

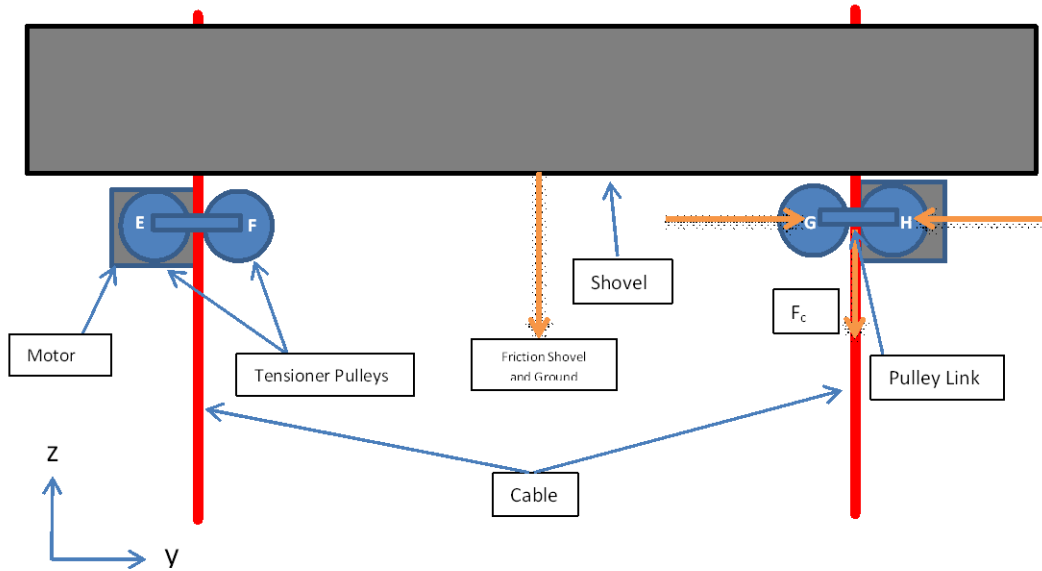
4.12 Design 7.5.3 - Cable Guided Shovel Actuator



Free Body Diagram



Z-Y Plane View (Bottom View)



- In this design the cable acts like a track. There are two holes on either side, and a double pulley tensioner allows the shovel to pull itself to either side of the driveway.

- The cable is in tension by being anchored at either side of the driveway.

Snow Weight

$d_{\text{driveway}} := 4.57\text{m}$ This is the horizontal distance (width of driveway)

$\rho_{\text{snow}} := 800 \frac{\text{kg}}{\text{m}^3}$ For slushy snow

$h_{\text{snow}} := 2\text{cm}$

$\text{Width}_{\text{shovel}} := 0.6\text{m}$

$\text{Area}_{\text{clear}} := \text{Width}_{\text{shovel}} \cdot d_{\text{driveway}} = 2.742\text{m}^2$

$V_{\text{snow}} := (\text{Area}_{\text{clear}} \cdot h_{\text{snow}}) = 0.055\text{m}^3$

$M_{\text{snow}} := \rho_{\text{snow}} \cdot V_{\text{snow}} = 43.872\text{kg}$

$W_{\text{snow}} := M_{\text{snow}} \cdot g = 430.237\text{N}$

Shovel Weight

Material : Alloy Steel, mass calculated by SolidWorks

$M_{\text{shovel}} := 9.67\text{kg}$

$W_{\text{shovel}} := 9.67\text{kg} \cdot g = 94.83\text{N}$

Other Weights

$M_{\text{other}} := 2\text{kg}$

$W_{\text{other}} := M_{\text{other}} \cdot g = 19.613\text{N}$

Friction between Shovel and Ground

$N_s := W_{\text{shovel}} + W_{\text{other}} = 114.444\text{N}$

Kinetic friction between steel and concrete $\mu_s := 0.75$

Friction factor obtained from $F_{\text{sg}} := \mu_s \cdot N_s = 85.833\text{N}$
(http://www.academia.edu/5307385/WTC2005-63579_FRICTION_BETWEEN_STEEL_AND_ASPHALT_WITHOUT_GOUGING_UNDER_REPRESENTATIVE_IMPACT_PRESSURES)

Work done to overcome shovel friction

$W_{\text{sg}} := F_{\text{sg}} \cdot d_{\text{driveway}} = 392.255\text{J}$

Friction Force On Pulley/ Cable

For this design we will take the material of the pulley and the cable to be rubber. I chose rubber because the coefficient of friction between rubber and rubber is 1.15, which is very high.

$$\mu := 1.15$$

Larger μ helps maintain contact between the pulley and the cable so that a smaller normal force required to maintain the same amount of traction.

$$N_{pc} := 15\text{N}$$

$$\text{Friction force on Cable, } F_{pc} := \mu \cdot N_{pc} = 17.25\text{N}$$

Assuming a Normal Force at points, E, F, G and H onto the cable,

$$\text{Work done to overcome friction between pulley and cable } W_{pc} := 2F_{pc} \cdot d_{\text{driveway}} = 157.665\text{J}$$

(It's $2 \cdot F \cdot c$ because there are two cables)

Friction Between Snow and Ground

$$\mu_s := 0.50$$

$$F_s := \mu_s \cdot W_{\text{snow}} = 215.119\text{N}$$

$$W_s := F_s \cdot d_{\text{driveway}} = 983.092\text{J}$$

Choosing Electric Motor

$$\text{Total Work required to overcome Friction, } \Sigma W := W_{sg} + W_{pc} + W_s = 1.533 \times 10^3 \text{ J}$$

$$P = \frac{\tau \cdot (2\pi \cdot n)}{60s}$$

where τ is torque and n is the rpm

$$P := \frac{\Sigma W}{30s} = 51.1\text{W}$$

30 seconds is the total time we are allotting the motor to fully compress the spring

if we assumed that the shaft had an rpm of 60 $n := 60$

$$P = \frac{\tau \cdot (2\pi \cdot n)}{60s} \text{ solve, } \tau \rightarrow 8.132885497358202258\text{N}\cdot\text{m} = 8.133\text{N}\cdot\text{m}$$

$$\text{Torque of Motor has to be } \tau = 8.1\text{N}\cdot\text{m}$$

Moment

- In the first FBD there is a net moment that occurs as a result of F.cable on the top and F.cable and F.snow on the bottom

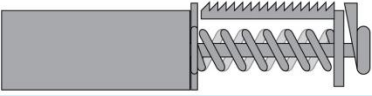
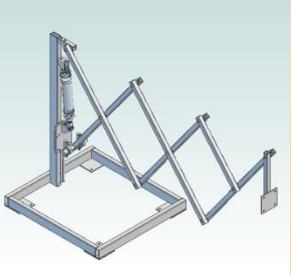

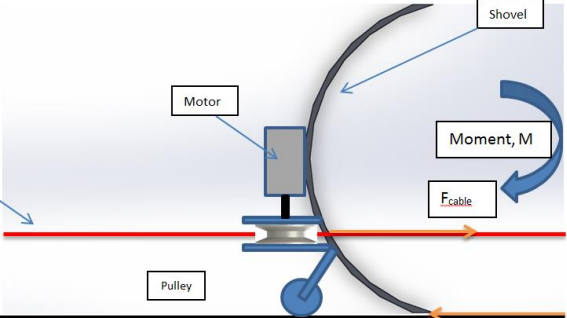
Max Force in System

- To counteract this, it was discussed that the weight in the pulley apparatus region should be increased, which would cause counteractive moment.

The Max Force gets transferred through the cables as the motor tries to overcome the friction forces.

$$\boxed{F_{\max} := F_{sg} + 2 \cdot F_{pc} = 120.333\text{N}}$$

4.13 Max Force Within Actuator

	Max Force Within System
<p data-bbox="402 323 699 394">Spring Loaded Launcher (Chameleon Design)</p> 	<p data-bbox="1052 401 1170 443">593 N</p>
<p data-bbox="383 554 716 583">Scissor Arms w/ Screw Jack</p> 	<p data-bbox="1040 709 1182 751">5943 N</p>
<p data-bbox="448 915 651 945">Telescopic Arms</p> 	<p data-bbox="1045 1108 1177 1150">304 N</p>
<p data-bbox="427 1394 672 1423">Rope Pulling Shovel</p> 	<p data-bbox="1024 1587 1198 1629">120.33 N</p>

After the calculations, it turned out that the “Rope Pulling Shovel” or [Cable Guided Shovel-Design \(7.5.3\)](#) was the best one, in terms of internal forces. It is also the second cheapest of the designs, the first being the Spring Launcher. The following sections will be about the prototype and its testing.

Chapter 5: Materials for Cable Guided Shovel Device

Some of the materials that were required for building this device were bought and some were acquired from the robotics lab in Atwater Kent and some I had at home. Below is a list of the items that were used to build the device and its testing setup.

- 1) Heavy Duty Adjustable Rolling Snow Pusher With 6" Rubber Wheels (\$59.99)



Figure 4 - Shovel Blade

- 2) Chemical-Resistant Polyurethane Cord 1/4" Diameter (\$18.50 for 25ft)



Figure 5 - Polyurethane Cord

3) Shaft Collar, 16 Pack (\$7.99)



Figure 6 - Shaft Collars

4) Shaft Coupler, 5 Pack (\$4.99)



Figure 7 - Shaft Couplers

5) Gusset Pack (\$7.49)



Figure 8 - Gussets

6) Drive Shaft Pack (\$5.49)



Figure 9 - Drive Shafts

7) Bearing Flat, 10 pack (\$4.99)



Figure 10 - Plastic Bearings

8) Aluminum C-Channel 1x3x1x35, 8 pack (\$37.99)



Figure 11 - C Channel

9) Nut 8-32 Hex, 100 pack (\$2.99)



Figure 12 - Nut

10) Screw 8-32 x 0.750", 100 pack (\$9.99)



Figure 13 - Screw

11) 12V DC Motor 251rpm (2 Motors) GB37Y3530-12V-251R. (\$29.00 for 1-> \$58.00 total)



Figure 14 - Motor

12) 18-2 Silver Stranded Lamp Wire (\$3.70)



Figure 15 - Co-Axial Power Cord

13) Eyebolt, 1/2-13, 1In, Turned Wire (\$1.52 for 4-> \$6.08)



Figure 16 - Eye Bolt

14) White Wood Studs (\$2.49 for 2-> \$4.98)



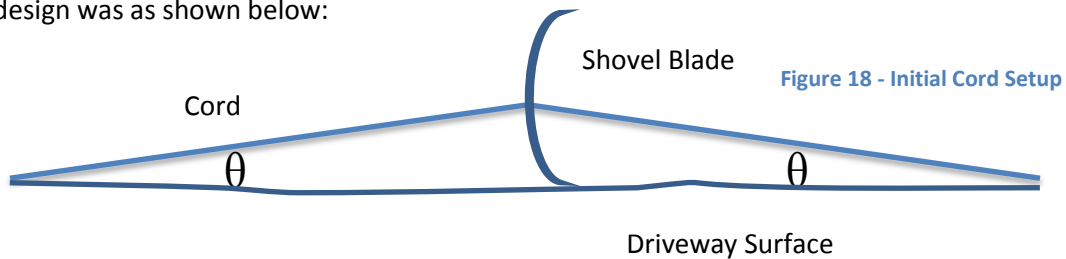
Figure 17 - Wooden Studs

Total Cost: \$230.18

Chapter 6: Testing Setup

6.1 Cords

One of the main unaddressed elements in the design process was the fixture method for the cords. The initial design was as shown below:



However three major changes were made to this:

- 1) The area where the edges of the holes on the shovel blade meet the polyurethane cord, high frictional forces were developing. This was not only an added opposing force on the motors but also the friction would wear away the cord, making it more likely to fail under high tension. Therefore during setup it was decided that the cord would not be fixed at an angle to the floor surface but parallel to it.

An added advantage was that the cord gripping assembly now received the cord at one set position as opposed to varying angles depending on the position of the device relative to the fixed ends of the cord.

- 2) The cord ended up being tensioned to 182 N, 76 N higher than original calculations (calculations follow). This was necessary because the diameter of the cord was 6.35 mm, whereas there was only a gap of 2mm at the CGA. The stretching was required to decrease the diameter of the cord down to 3mm.

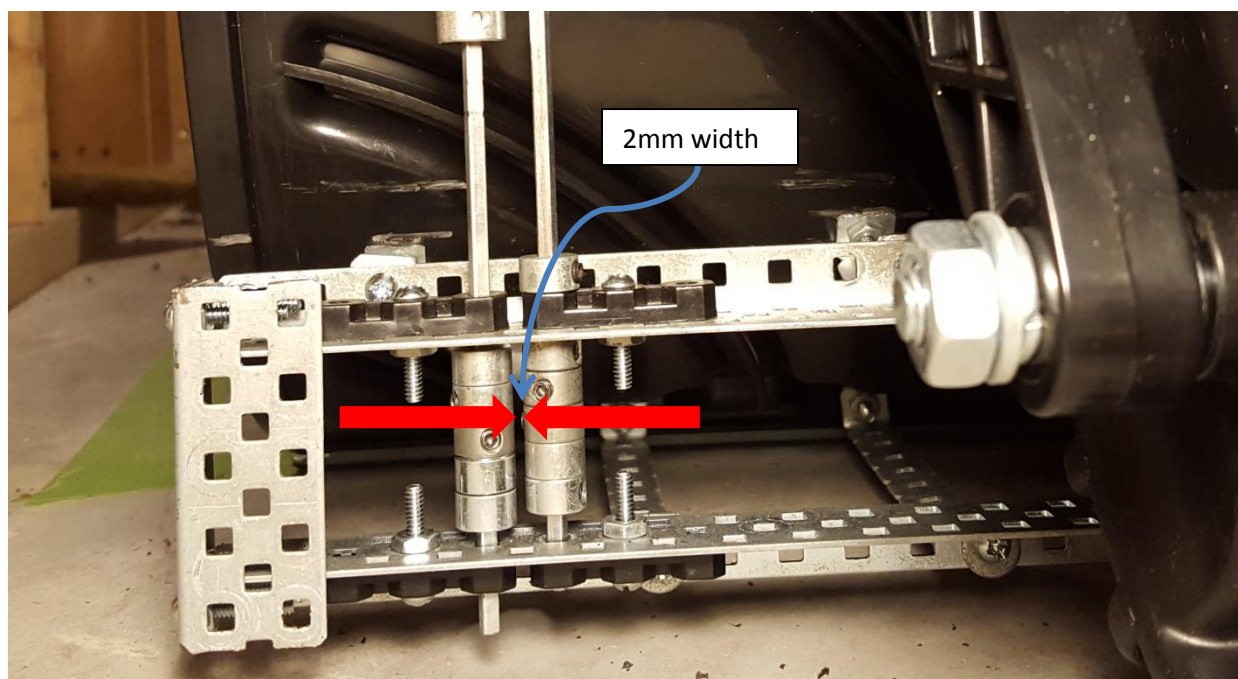


Figure 19 - Cord Gripping Assembly (CGA), both shafts go through a set of 5 Shaft Collars (Pulleys)

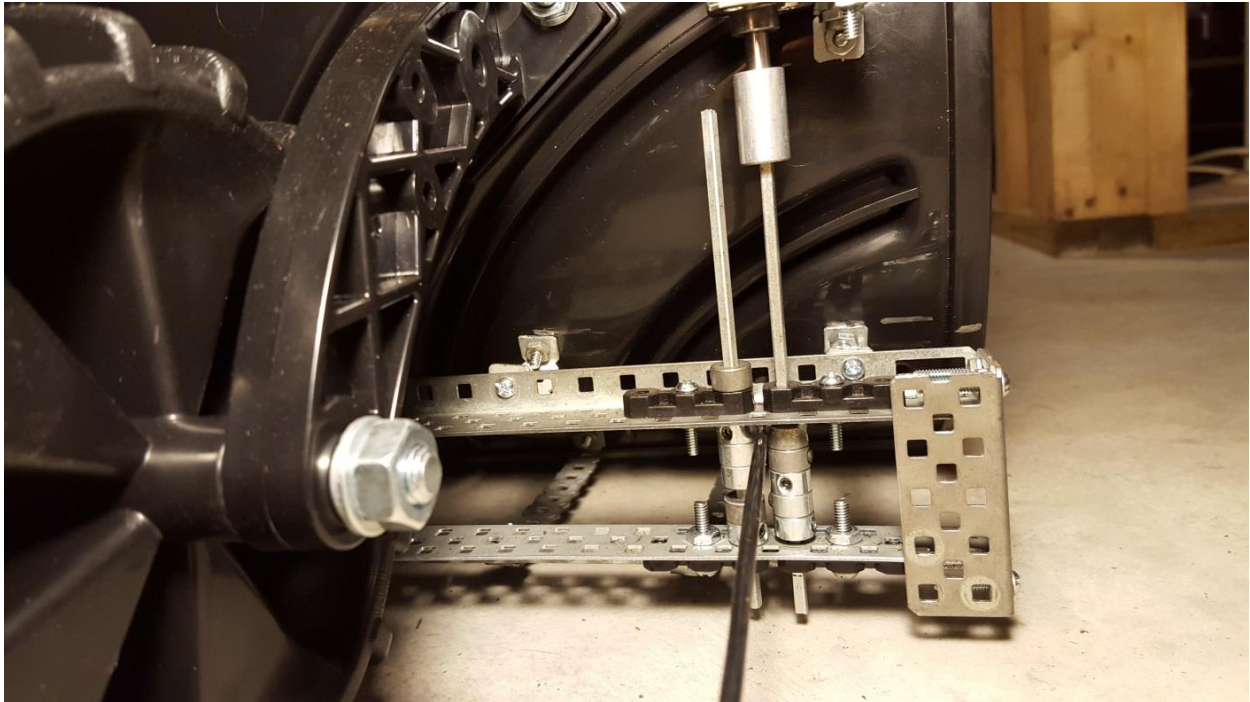


Figure 20 - Right CGA with Tensioned Polyurethane Cord Running Through



Figure 21 - Visible Difference of Tensioned Cord

- 3) And because of this increased tension force, fixture methods based on stakes in the ground were not going to be enough to hold the cord rigidly. Therefore the whole fixture methods was implemented as such on concrete floors with the help of staircase support frames:



Figure 22 - Making Use of Stairwell Support for Experimental Setup



Figure 23 - Back View of Setup

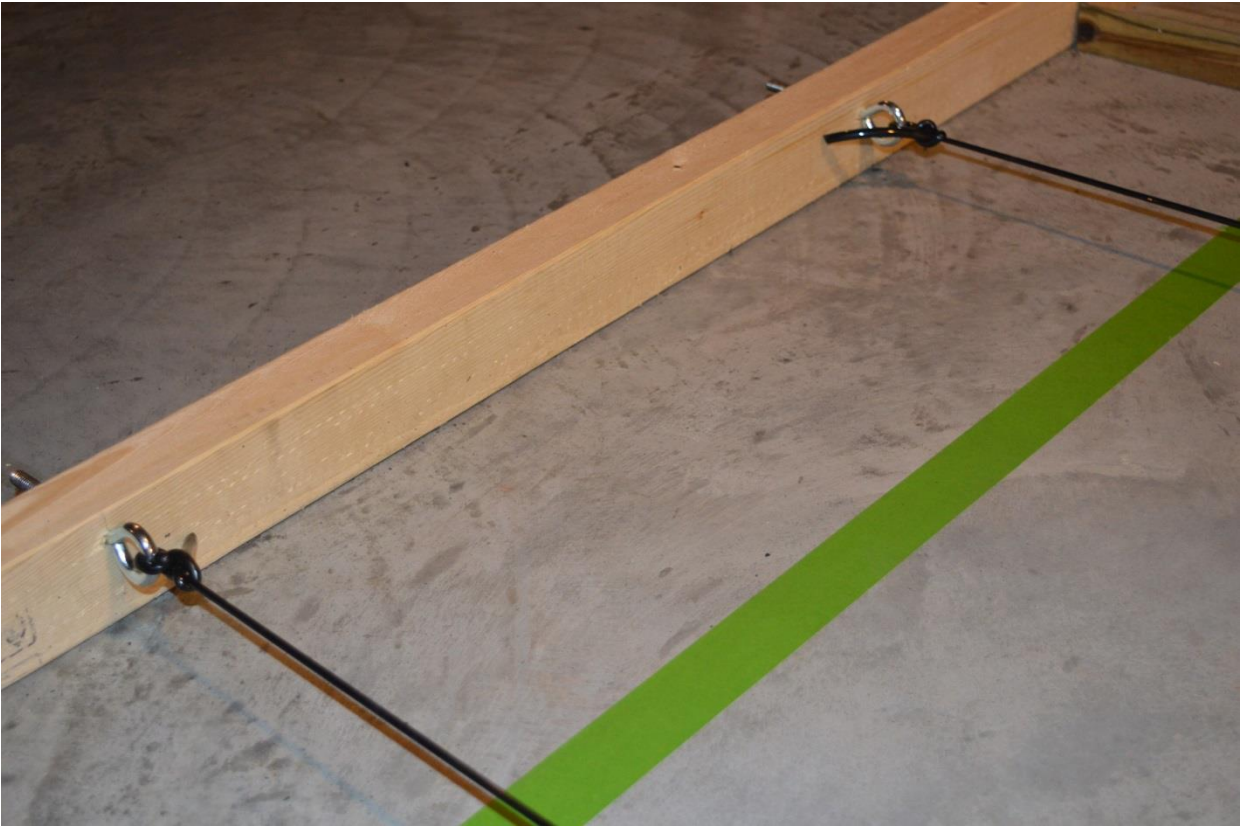


Figure 24 - Eyebolts Used to Connect Cord to Wooden Studs

As shown above, two eyebolts were drilled into a wood stud which then was placed behind the staircase support frame, with one stud at each end of the clearing path. The polyurethane cord was then looped through the device, tied to both studs and tightened until there was an optimal gripping force as well as easy movement at the CGA.

6.1.1 Calculations For Actual Tension in Cord (Device off)

Given:

- 1) The initial and final lengths of the cord are l_i and l_f , respectively
- 2) The elastic modulus of the Polyurethane cord, E_1 (Engineering-Toolbox, 2016a)
- 3) Diameter of the stretched cord, d

$$l_f := 2.4606\text{m} \quad l_i := 1.2128\text{m} \quad \Delta l := l_f - l_i = 1.248\text{m}$$

$$E := 0.025 \text{ GPa} = 25 \cdot \text{MPa}$$

$$\sigma = \frac{F}{A}$$

$$\sigma := E = \frac{\sigma}{\left(\frac{\Delta l}{l_i}\right)} \text{ solve, } \sigma \rightarrow 2.5721470976253298153\text{e}7\text{Pa} = 25.721 \cdot \text{MPa}$$

$$d := 3\text{mm} = 3 \times 10^{-3} \text{m}$$

$$A := \frac{(\pi \cdot d^2)}{4} = 7.069 \times 10^{-6} \text{m}^2$$

Solving for F we get the tension within the cord:

$$F := \sigma = \frac{F}{A} \text{ solve, } F \rightarrow 181.81436458167089931\text{Pa} \cdot \text{m}^2 = 181.814\text{N}$$

6.1.2 Calculations for Depth of Indentation of Cord in CGA for Generating Appropriate Friction

Since the cord needed to be gripped between the Shaft Collars to generate sufficient friction, we needed to know how much the cord need to be compressed by the shaft collars when it is pulled through the CGA. Since this was a contact mechanics problem, we used the depth of indentation formula based on the contact area between a sphere and plane.

Given:

- 1) Opposing Frictional Force, F_f
- 2) Radius of the Cord, d
- 3) Elastic Modulus of the Polyurethane and Shaft Collar, E_1 and E_2
- 4) Poisson's Ratio of Polyurethane and Shaft Collar, ν_1^2 and ν_2^2 (Boyce, 2003) and (Engineering-Toolbox, 2016b)

The Depth of Indentation is given by the formula:

$$d = \left(\frac{9F^2}{16RE^*} \right)^{1/3}$$

(Wikipedia-Contributors, 2016)

The Adjusted Elastic Modulus is Given by:

$$\frac{1}{E^*} = \frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2}$$

$$F_f := 158.65\text{N}$$

The frictional force bore by a single shaft (there are 4 shafts, with shaft collars on them, 2 shafts in each CGA, 2 CGA's on either side of the shovel blade, please refer to Figures 19 and 20)

$$F_{\text{single}} := \frac{F_f}{4} = 39.663 \text{ N}$$

Elastic Moduli and Poisson's Ratios of Polyurethane (E_1, ν_1) and Steel (E_2, ν_2)

$$E_1 := 25\text{MPa}$$

$$E_2 := 200\text{MPa}$$

$$\nu_1 := 0.49$$

$$\nu_2 := 0.28$$

Radius of the Polyurethane Cord

$$R_{\text{cord}} := 0.003\text{m}$$

Adjusted Elastic Modulus

$$E' := \frac{1}{\frac{1}{E'} = \frac{(1 - \nu_1^2)}{E_1} + \frac{(1 - \nu_2^2)}{E_2}} \text{ solve, } E' \rightarrow 28.568163638441320992\text{MPa}$$

Solving Equation for Depth of Indentation by one Collar

$$d := \left(\frac{9 \cdot F_{\text{single}}^2}{16 \cdot R_{\text{cord}} \cdot E'^2} \right)^{\frac{1}{3}} = 0.712 \cdot \text{mm}$$

Total Compression between 2 Collars

$$d_{\text{tot}} := d \cdot 2 = 1.425 \cdot \text{mm}$$

Thus, the optimal compression of the cord would have been about 1.43mm. This was 0.43 mm higher than the actual achieved compression of 1mm. The initially calculated opposing friction force of 158 N was based on much heavier device than the one finally assembled. So the compression was probably much higher than required. As for the tension in the cord, it needed to be tensioned that high to stretch the 6.35 mm diameter cord to about 3mm so that it could fit between the 2mm gap of collars in the CGA, it's not that the tensioning actually had to be that high.

6.2 Electrical

The electrical wiring for this device is as shown below:

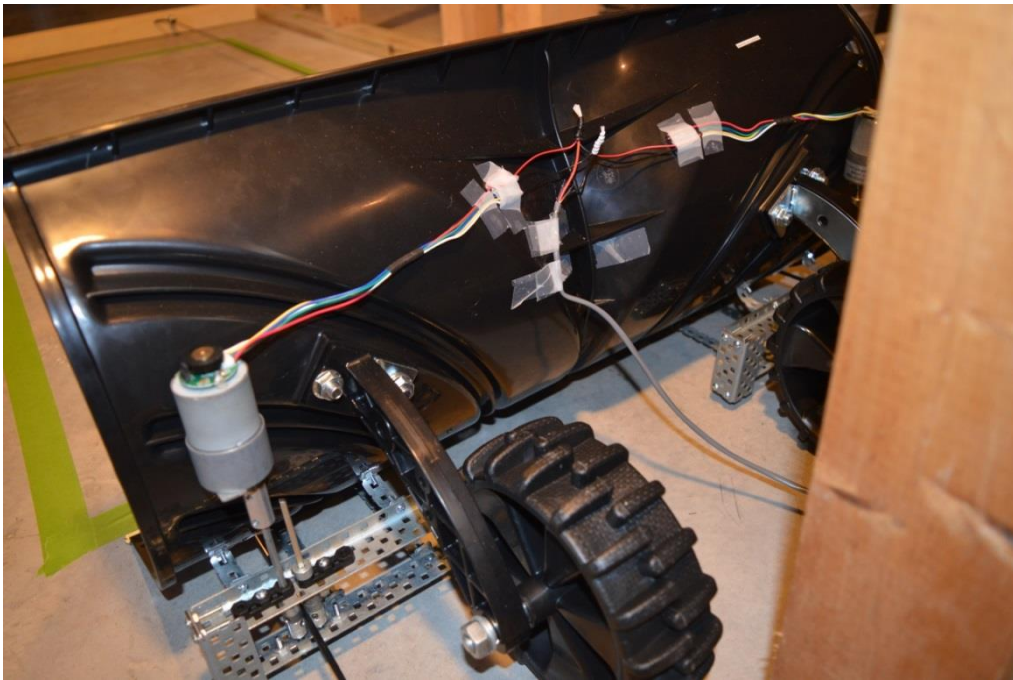
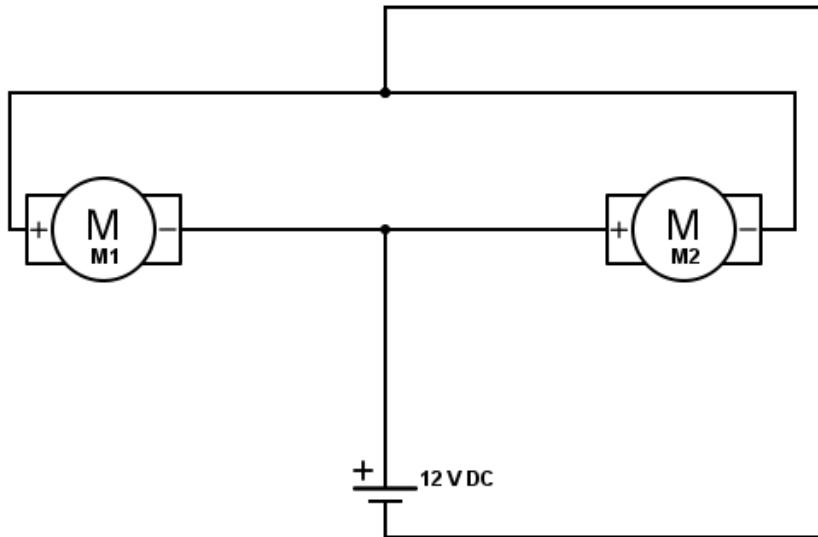


Figure 25 - Wiring of Motors in Parallel to Power Supply

It is important to note that the polarity of the connecting wires of the motors are switched. This is because they are placed on the opposite sides of the CGA so that if the device is to move forward, the motor on the left needs to turn in a counterclockwise manner whereas the motor on the right, clockwise.

The motors (DF Robot GB37Y3530, 251 RPM) were powered using a 12V AC adapter as per power rating requirements for that model. They were wired in a parallel setup because the motors were rated to run at 250 RPM at 12V which was too fast for this application. Wiring them in parallel helped to reduce the RPM. Under load, the motors had an RPM of about 40. Not only was the parallel wiring responsible for lowering the RPM but there were also significant friction forces at the plastic bearings as a result of the 3mm cord pushing against the shafts which rubbed on the plastic bearings increasing rotational friction. The calculations for the RPM under load are shown below and tabulated in Table 1.

6.2.1 Calculations for Shaft RPM Under Load

Given:

- 1) Diameter and circumference of the shaft collars, d and c respectively
- 2) Length of the clearing path, l
- 3) Average time taken for forward cycle, t

Since the motor shaft goes through the shaft collars, the diameter of the collars was needed because the collars were in direct contact with the cord. First the diameter and circumference of the collar is calculated.

$$d := 11\text{ mm} = 0.011\text{ m} \quad c := \pi \cdot d = 0.035\text{ m}$$

The length of the clearing path is used to determine the number of revolutions in one cycle.

$$l := 0.9525\text{ m}$$

$$\text{revs} := \frac{l}{c} = 27.563$$

Number of revolutions are divided by the average time it takes for one forward cycle, then the RPM is found.

$$t := 42.39\text{ s}$$

$$\frac{\text{revs}}{t} = 0.65 \frac{1}{\text{s}}$$

$$\text{RPM} := \left(\frac{\text{revs}}{t} \right) \cdot 60 = 39.013 \frac{1}{\text{s}}$$

Also, a simple “direction controller” was made so that the user could control the direction of the device, forward and back by switching the polarity. It is controlled by taking the positive and neutral wires from the 12V AC adapter and touching the wires on the controller to go in one direction and reversing the

wires to go in the opposite direction.

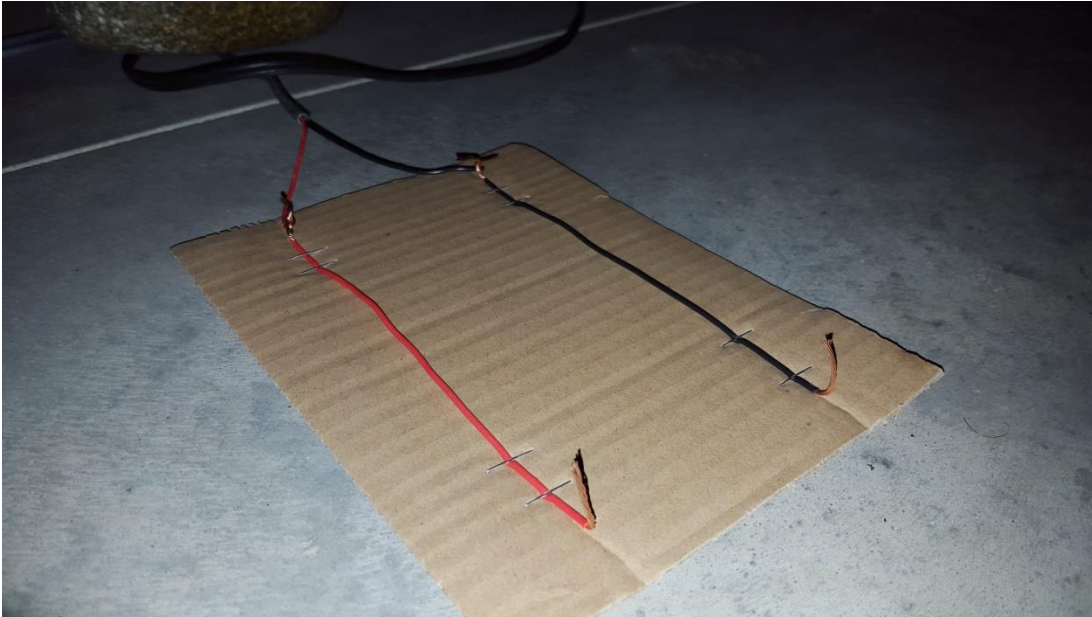


Figure 26 - Direction Controller



Figure 27 - 12 V AC Adapter

6.3 Clearing Path

The path that was delineated to be cleared was done using green tape as shown below. Initially the clearing path was 67.31cm X 178.43cm, but the dimensions were changed (length only) to 67.31cm X 95.25cm to facilitate clean up between trials thus reducing the amount of time for each trial. That's why there are two rectangular boxes on the clearing path. Therefore only the first box was the one that was used for testing.



Figure 28 - Mulch Spread into the Actual Testing Box

6.4 Mulch as Snow Substitute

The first prototype was finished in April, however the snows had stopped by that time. Therefore testing required the use of some other form of material which was similar to snow; wood mulch was chosen as this material. Dry wood mulch has a density similar to that of wind packed snow, 380 kg/m^3 (Aqua-Scale, 2016). With mulch, multiple tests could be conducted on the path just by rearranging the mulch back onto the path after each trial. Also the present prototype necessitated the use of something other than snow, because of the possibility of a shorting due to the infiltration of water into the wiring or the motors was very likely.



Figure 29 - Graduated Plastic Mug Used to Measure Mulch

6200 ml (2.356 kg) of mulch were spread at a thickness of $9\text{mm} \pm 2\text{mm}$ onto the clearing path. The mulch had to be carefully spread within the dimensions of the clearing path marked by the green tape. It had to be spread evenly onto the entire surface so that there was a uniform thickness that simulates snow accumulation. After the mulch was carefully placed, the device was then powered to move forward till it reached, then reversed till it reached the home position. At this point the amount of left over mulch on the path that falls within the inside border of the green tape would be gathered into a graduated cylinder mug, measured and recorded. Next the mulch would be rearranged onto the path for the next trial. This process was done 5 times.



Figure 30 - Mulch Spread a About a Thickness of 9mm

Chapter 7: Testing & Observations

Five trials were conducted in the manner outlined above. The time the device took for each forward and reverse cycle was recorded and RPM for both cycles calculated. Then the remaining mulch in the path would be gathered and measured. Table 1 below shows the time required for forwards and reverse cycles, their velocities, the initial and final mulch amounts in the clearing path, the removal efficiencies, mass of the mulch cleared, and finally the work done in remove that mass. Finally the average and standard deviation were calculated for each parameter.

Table 1

Trial #	Time for Forward Cycle (s)	Time for Reverse Cycle (s)	Velocity Forward (m/s)	Velocity Reverse (m/s)	Motor RPM (Forward Cycle)	Motor RPM (Reverse Cycle)
1	46.34	48.17	0.020554596	0.019773718	35.68762505	34.3318361
2	46.95	49.61	0.02028754	0.019199758	35.22395197	33.33530629
3	46.68	48.65	0.020404884	0.019578623	35.42768948	33.99310473
4	37.88	39.38	0.025145195	0.024187405	43.65798693	41.99503669
5	34.12	37.62	0.027916178	0.025318979	48.46906638	43.95971677
Data Analysis						
Average	42.394	44.686	0.022861679	0.021611697	39.69326397	37.52300012
Standard Deviation	5.990265437	5.704807622	0.003490955	0.002902896	6.061121075	5.040111638
Ave ± SD	42.39 ± 5.99	44.67 ± 5.70	0.0228 ± 0.003	0.0216 ± 0.003	39.7 ± 6.06	37.52 ± 5.04

Trial #	Mulch Initial (m ³)	Mulch Final (m ³)	Removal Efficiency (%)	Mass of Mulch Cleared (kg)	Work Done (J)	Power (W)
1	0.0062	0.00061	90.16129032	2.1242	24.6981183	0.53297623
2	0.0062	0.00079	87.25806452	2.0558	24.30185689	0.51761144
3	0.0062	0.00071	88.5483871	2.0862	24.47797307	0.52437817
4	0.0062	0.000605	90.24193548	2.1261	24.70912556	0.65230004
5	0.0062	0.00063	89.83870968	2.1166	24.65408926	0.72257003
Data Analysis						
Average		0.000669	89.20967742	2.10178	24.56823262	0.58996718
Standard Deviation		7.97183E-05	1.285778288	0.030292936	0.175495933	0.09253937
Ave ± SD		0.000669 ± 7.8E-05	89.21 ± 1.29	2.101 ± 0.03	24.57 ± 0.18	0.59 ± 0.09

7.1 Device Velocity

The device took an average of 0.0228 m/s (2.28 cm/s) to complete the forward cycle and 0.0216 m/s (2.16 cm/s) to complete the reverse cycle. This was interesting because it had a higher velocity under the opposing force of the mulch than it did on the reverse cycle. This was interesting because the opposing force of the mulch was a fraction of the initial mulch load on the reverse cycle. I suspect that this may have been because of a misalignment of the cords, because the device would twist to the right *only* on the reverse cycle thus causing excessive friction to develop on right CGA. Or it also might have been because of a difference of tensioning between the two cords thus causing different gripping frictions at the CGA's. However this is still curious that it should happen on only the reverse cycle.

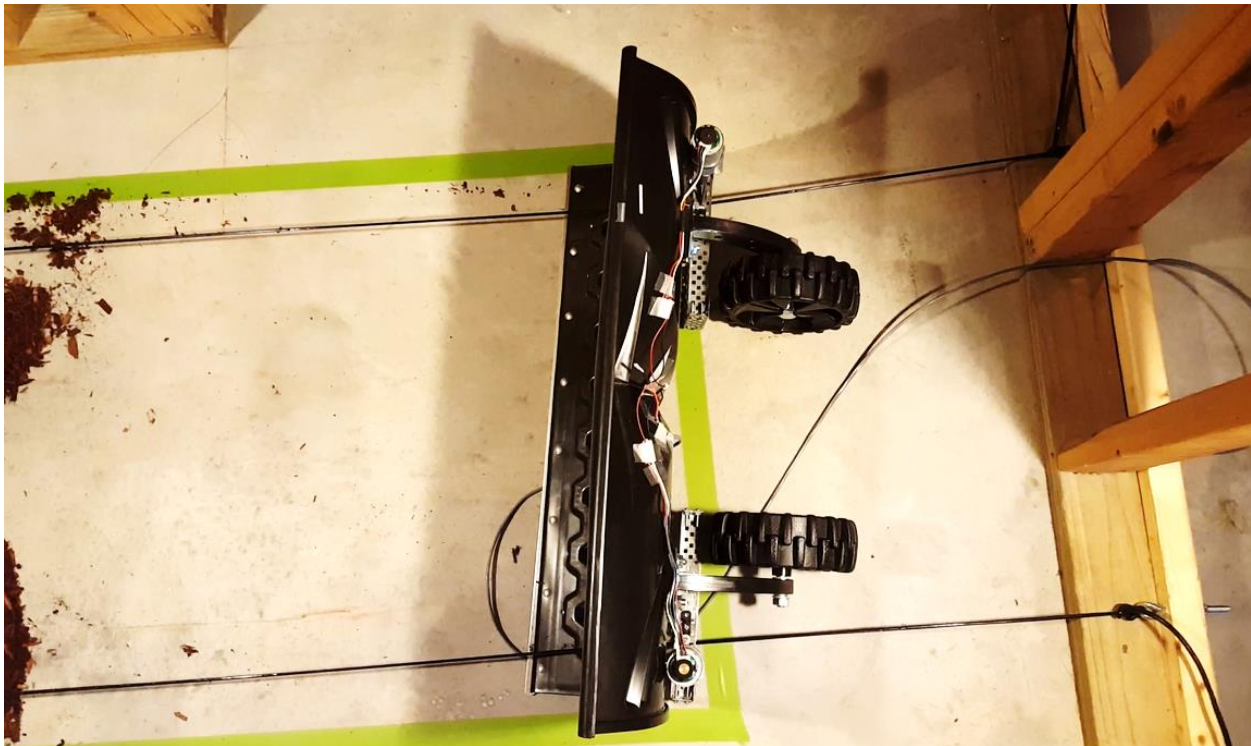


Figure 31 - Twisting of Device to Its Right on Reverse Cycle

The image above shows a top view of the device twisting to the right. Although one might point out that the source of this twisting might be the power cord under left side of the shovel blade, this twisting occurred even when the wire was not under the blade. It just so happened to go under the blade as I was taking a top view picture. The power cord needs to be pulled out of the way as the device reverses into the home position.

Another interesting observation was that the time required for the forward cycle in the first three trials took about 9-12 seconds longer than the last two trials. The only reason I can see why this occurred was because of varying current usages in the house. As I remember the drier and washing machine were running for a period of the time that the experiment was being conducted. This might have caused the voltage to drop. I know this because whenever the space heater or drier in the house is turned on, the lights become noticeably dimmer.

7.2 Removal Efficiency

On average the device cleared about 89.21% of the initial mulch “accumulation” from the clearing path with the remaining parts shoved to the front and side of the path. A majority of the efficiency loss came as a result of left over mulch on the shovel tip as it reversed back to the home position. Without this, I suspect the efficiency would have been much closer to 100% because the remaining mulch on the clearing path were very small pieces as shown in the image below.



Figure 32 - View of Clearing Path After Forward Cycle



Figure 33 - Top View of Clearing Path After Forward Cycle

7.3 Work & Power

The value for work was calculated based on the forward cycle, because useful work was done only during the forward cycle. The reverse cycle is only required to bring the device back to the home position. The maximum work done was 24.71 J in Trial # 4 and the min work done was 24.30 W in Trial # 2. The average work done by the motors was calculated to be 24.57 J. This was lower than the initially calculated value of 190 J by 165 J. The 190 J was also calculated only for the forward cycle. The major contributing factors to this were three fold:

- 1) The shovel blade as initially designed was not metal but plastic, thus reducing the weight dramatically. The whole weight for the final assembly weighed 2.948 kg while initial shovel blade estimates alone reached 10kg.
- 2) The length of the clearing path was decreased by about 0.2475m
- 3) The coefficient of friction between the snow and asphalt of 0.75 was changed to a coefficient of friction of 0.62 between the mulch and concrete. And the coefficient of friction within the snow was not required anymore. A new coefficient of friction between the steel edge of the shovel and concrete of 0.45 was introduced.

From Table 1 we can see the max power developed was 0.723 W in Trial # 5 and the minimum was 0.518 W developed in Trial # 2. The average power developed by the device was calculated to be 0.589 W. The average value was extremely low compared to the initial estimate of 19 W, as a matter of fact it was only 3.1% of the initial estimate. Two of the major reasons for this was because:

- 1) The cycle period for the device was increased dramatically by more than 3-4 times as much from 10s to 36s-47s.
- 2) The weight of the device went up, clearing path area decreased, and coefficients of friction also decreased, as discussed above in the work section.

And since the power is dependent on time we can see a clear correlation between the power and velocity. The power increases in the last two trials since velocity is directly proportional to power

7.3.1 Calculations for Work and Power

Friction Between the Steel Shovel Tip and Concrete Floor

Given

- 1) Length of the clearing path, d
- 2) The coefficient of friction between the steel shovel tip and concrete, μ_d
- 3) Mass of the whole device, m_d

$$d := 95.25 \text{ cm} = 0.953 \text{ m}$$

$$m_d := 2.948 \text{ kg} \quad F_d := m_d \cdot g = 28.91 \text{ N} \quad \mu_d := 0.45$$

$$W_d := F_d \cdot d \cdot \mu_d = 12.392 \text{ J}$$

Friction Between the Wood Mulch and Concrete Floor

Given

- 1) Length of the clearing path, d
- 2) The coefficient of friction between the wood mulch and concrete, μ_m
- 3) Mass of the mulch depends on the Trial number; here we will be taking the average value of $m_m = 2.101 \text{ kg}$

$$m_m := 2.101 \text{ kg} \quad F_m := m_m \cdot g = 20.604 \text{ N} \quad \mu_m := 0.62$$

The work done to overcome the friction between the mulch and concrete is given by W_m

$$W_m := F_m \cdot d \cdot \mu_m = 12.168 \text{ J}$$

Total Work for Opposing Force and Power

Assuming that the average time for a forward cycle is t

$$t := 42.39 \text{ s}$$

$$W_{\text{tot}} := W_{\text{d}} + W_{\text{m}} = 24.559 \text{ J}$$

$$P := \frac{W_{\text{tot}}}{t} = 0.579 \text{ W}$$

Chapter 8: Conclusion & Recommendations

As a conclusion, I think the whole design to prototype process went well. There were some initial troubles such as getting to understand the purpose of the Design Decision Matrix in the design process but I came to understand the benefits of a quantitative versus qualitative approach to the design process. Also, I learned about the importance of coming up with several viable ideas. It allows the best idea to be chosen while aiding in the development and improvement of existing ideas. I was also pleased that the prototype that was assembled was very similar to the one designed and was also strong enough to clear the mulch with ease. I am sure it could have handled loads three times as much as ones used for testing. And with the use of lower RPM, large gear ratio motors, I believe this device can be easily upgraded to taken on much larger loads.

I learned how a systematic approach could be taken right from designing the device to force analysis and energy analysis of the device. We analyzed preliminary designs so that they can be individually tested and the best design could be chosen based on quantitative and empirical data. I was intrigued by the fact that there are formulas that can tell me how much a material needs to be indented to produce the appropriate frictional force.

A defect that needs to be addressed is the twisting motion that occurs on the reverse cycle. The source of the problem doesn't seem to be clear. While it could be because the cords are not aligned parallel to each other, the twisting never occurs in the forward cycle. If it is because of varying tension within the cords, I should be able to observe that in the forward cycle, which I don't.

With regards to the practicality of this device, two major problems are that the design wasn't advanced far enough to develop water proofing ideas for the electrical parts, making it non-operable for its intended use, clearing snow. And the second was that the device once setup on the driveway has no easy method to temporarily remove it to allow for traffic. This is because the cords are in tension and the supports which they are tied to will be fixed. These two aspects highly diminish the practicality of the device.

Some things to keep in mind when testing in the future is to use a power source that does not vary due to voltage fluctuations in a building. To set the right amount of tension in the cord there should be a better method to measure the elongation, using precise instruments and not sharpie markings like I had to resort to. To avoid the blades getting stuck on rough surfaces on the ground, the end of the blade should be made more rounder to help facilitate more efficient snow removal without the device getting stuck.

For videos taken in the Testing, please follow this link: bit.ly/1rhBe0j

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