January 25th, 2020

Goal: Calculate expected mass flow rate using the CO_2 cartridge

Mass flow rate for a cold gas propulsion system where the gas is expelled from a small orifice can be calculated using the choked flow equation. This equation can be used for CO_2, when the pressure in the tank is at least 2x the ambient pressure. Since the pressure in the tank is 57 atm, which is more than 50 times the ambient pressure, we can use the choked flow equation to figure out the mass flow rate:

$$\dot{m} = C_d A \sqrt{\gamma \rho_0 P_0 \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}}$$

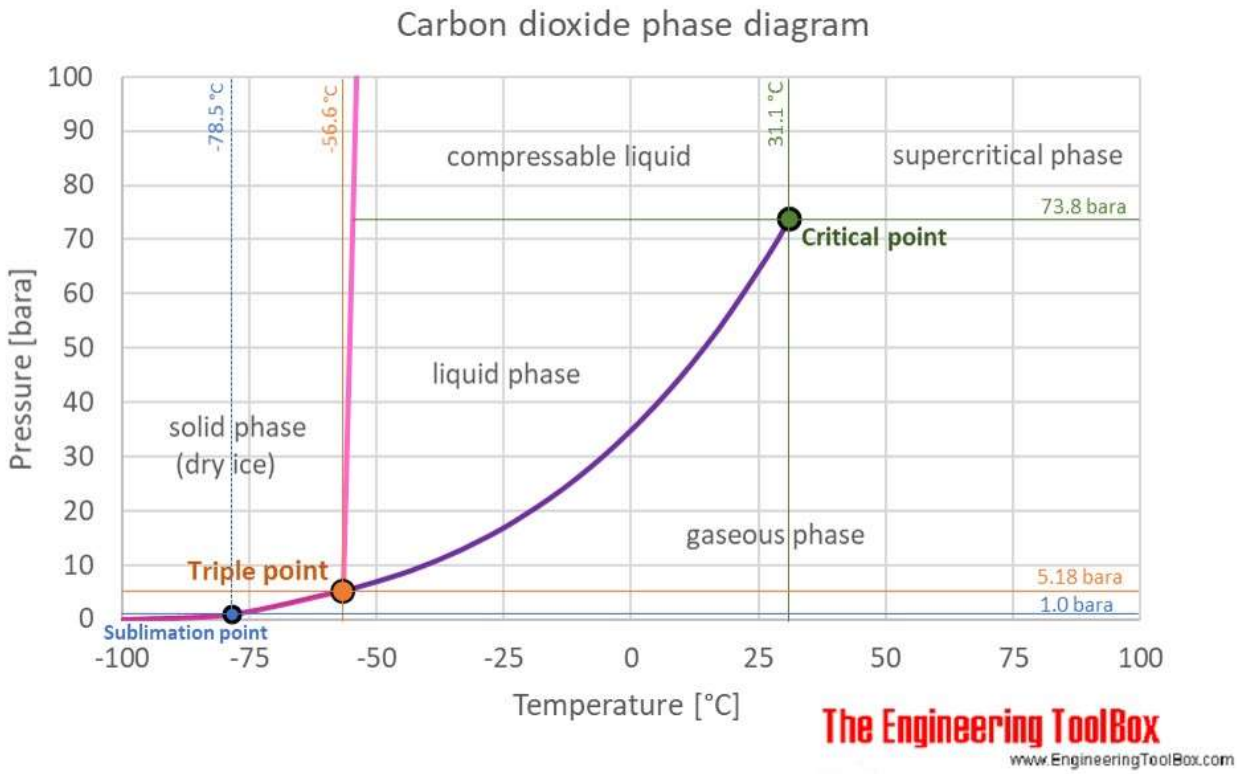
(Choked Flow Equation, n.d.)

Where:

- C_d = Discharge coefficient.
  - Estimated value: 0.7 (based on online forum recommendation)
- A = area of the orifice the propellant comes out of
  - Estimated diameter of the orifice = 0.1 mm = 1×10^{-4} m
  - Radius = 0.5×10^{-4} m
  - Area = 7.85×10^{-7} m^2
- P_0 = pressure of the gas in the tank:
  - At 20°C, Pressure = 57 atm = 5.77×10^6 Nm^2.
    (http://www.energy.psu.edu/tools/CO2-EOS/index.php)
    (http://www.chemicalogic.com/Documents/co2_phase_diagram.pdf)
- ρ_0 = real gas density of the gas at pressure P_0 and Temperature T_0.
  - Online sources say: 192 kg/m^3
    (http://www.energy.psu.edu/tools/CO2-EOS/index.php)
- γ = specific heat ratio of the gas (= 1.3 for CO_2) (Choked Flow Equation, n.d.)

Based on these the expected mass flow rate should be: 12.27 g/s

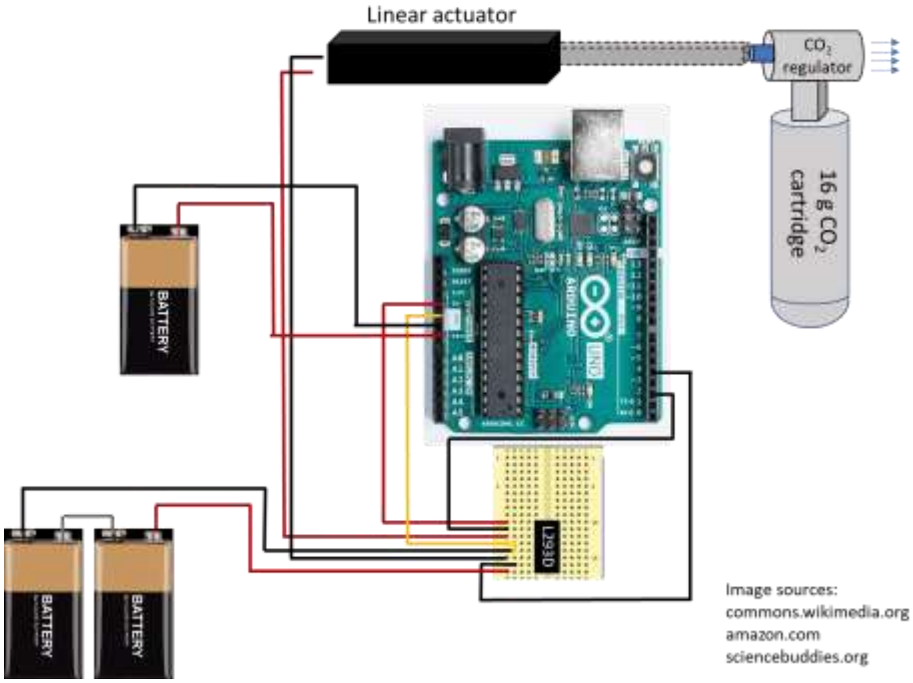
CO2 phase diagram (Source: engineeringtoolbox.com)


Carbon dioxide phase diagram
Pressure [bara]
Temperature [°C]
-78.5 °C
-56.6 °C
31.1 °C
compressable liquid
supercritical phase
73.8 bara
Critical point
liquid phase
solid phase
(dry ice)
gaseous phase
Triple point
5.18 bara
1.0 bara
Sublimation point
The Engineering ToolBox
www.EngineeringToolBox.com

January 26th, 2020

Goal: Assembling the initial robot to measure mass flow rate

- Verified the amount of force needed to depress the regulator button: a 7.5 lb (3.4 Kg) dumbbell can press it. So, we need linear actuator that can generate at least 3.4 x 9.8 = 34 N of force.
- Created the first prototype using linear actuator, connected using Arduino. Total weight: 428g.
- Wrote code to get the actuator to move forward and backwards to press and release the regulator.



- Measure the max impulse duration of the 16g CO_2 cartridge and the resulting mass flow rate. Comparing vs. the calculated value using the choked flow equation.

Variable	Calculated	Observed	Notes
Total impulse duration	1.4 s	Leaking regulator	The regulator is leaking, every time I attach a new CO_2 cartridge, the CO_2 starts leaking and the cartridge becomes empty.
Mass flow rate	12 g/s	Leaking regulator	Need to get a new regulator

January 28th, 2020

Goal: Measure the max impulse duration and the mass flow rate

- Got the new regulator
- Observed max impulse duration for the robot with the 16g CO_2 cartridge.
- Performed the experiment 3 times
- **Steps**:
    - Start the stopwatch timer on an iPad. The stopwatch timer has an accuracy of 1/100th of a second.
    - Begin recording the experiment in slo-mo video using an iPhone
    - Playback the video in slo-mo to observe stopwatch value when the CO_2 expulsion starts and stops.

Results:

1st Run:

Variable	Calculated	Observed	Notes
Max impulse duration	1.4 s	2.4s	The flow starts strong, but after about 1.2 seconds it starts slowing down before becoming empty.
Cartridge starting mass		59g	
Cartridge ending mass		43g	
Mass flow rate	12 g/s	6.6 g/s	Mass flow rate = (starting cartridge mass – ending cartridge mass)/Max impulse duration

2nd Run:

Variable	Calculated	Observed	Notes
Max impulse duration	1.4 s	2.3s	The flow starts strong, but after about 1.2 seconds it starts slowing down before becoming empty.
Cartridge starting mass		59g	
Cartridge ending mass		43g	
Mass flow rate	12 g/s	7.0 g/s	Mass flow rate = (starting cartridge mass – ending cartridge mass)/Max impulse duration

3rd Run:

Variable	Calculated	Observed	Notes
Max impulse duration	1.4 s	2.2s	The flow starts strong, but after about 1.2 seconds it starts slowing down before becoming empty.
Cartridge starting mass		59g	
Cartridge ending mass		43g	
Mass flow rate	12 g/s	7.3 g/s	Mass flow rate = (starting cartridge mass – ending cartridge mass)/Max impulse duration

Observations:

- CO_2 mass seems to be fairly constant at 16g. My weigh scale only has an accuracy of 1g.
- Average values:
  - Max impulse duration: 2.3 seconds
  - Mass flow rate: 7.0 g/s
- **Observed mass flow rate is only 57 % of the value** predicted by the choked flow equation. Possible reasons:
  - **Assumptions not valid**
    - **Constant pressure**: Choked flow equation assumes constant gas pressure. It doesn't seem that the pressure in the CO_2 cartridge is constant throughout. There is a visible slowdown after 1.2 seconds.
    - **Constant temperature**: Choked flow equation assumes constant temperature: The cylinder becomes extremely cold once the gas starts flowing. This lowers the pressure in the tank, which could affect the flow rate.
  - **Measurement error**:
    - Diameter of the orifice: the orifice measurement of 1mm is approximate because my ruler only has an accuracy of 1mm. If the orifice is smaller than 1mm, then the mass flow rate would be smaller.
  - **Observation error**:
    - **Time measurement**: The start and end time were observed visually. I used slo-mo to observe the value of the stopwatch, but there was definitely a possibility of error.

February 3rd, 2020

Goal: Measure temperature change in the gas cartridge during gas expulsion to see if it explains the difference in observed vs calculated mass flow rate

Steps:

- Measure the temperature of the CO2 cartridge before expelling CO2 (using a IR laser thermometer)
- Expel all the CO2 in the cartridge
- Measure the temperature of the CO2 cartridge after all the CO2 is expelled (use the same IR laser thermometer)

Results:

- Temperature before expelling CO2: 19.4°C
- Temperature after expelling CO2: 4°C

Observations:

- The temperature of the cartridge drops by 15.4°C
- At 4°C, both the pressure and density of CO2 are significantly reduced vs the starting temperature of 19.4°C:

	At 19.4°C	At 4°C
Pressure	57.1 atm	38.2 atm
Density	192 kg/m^3	111 kg/m^3

Source: http://www.energy.psu.edu/tools/CO2-EOS/index.php

- If we use the pressure and density values at 4°C as input to the choked flow equation, we get the following readings for max impulse duration and mass flow rate
  - Max impulse duration: 2.1 seconds
  - Mass flow rate: 7.6 seconds
- These values are very close to the observed rate and explain almost 90% of the discrepancy between predicted rate and the observed rate.
- There is a visible slowdown in the gas flow with time. It doesn't seem that the cartridge is maintaining constant pressure.

February 4th, 2020

Goal: Use "Lift" generated by helium balloons to balance Earth's force of gravity acting on the robot

Steps:

- Measure the mass of the robot using a weigh scale with at least 1g accuracy. Let's say it is M grams.
- Fill a large helium foil balloon (36" size) with helium and attach it to the robot.
- Measure the mass of the robot again, it should be less than in the first step.
- Calculate the difference vs the 1st step. Let's say it's reduced by x grams. This is the "Lift" generated by the balloon.
- The net upward buoyant force applied by the helium balloon is: xg mN, where g is the gravitational acceleration on Earth = 9.8 m/s^2.
- Divide M by x, this is equal to the number of balloons needed to completely balance the force of gravity on the robot. Number of balloons = M/x.

Expected Results:

- Lift that 1 balloon with V liters of Helium can generate = V/(ρ_A - ρ_H) grams
  Lift = V/(1.204 - .1634) g
  Lift = V/1.04 g
  Source: https://www.engineeringtoolbox.com/air-density-specific-weight-d_600.html
  https://www.engineeringtoolbox.com/helium-density-specific-weight-temperature-pressure-d_2090.html
- Capacity of the Helium balloon I'm using: 2.0 cu ft (source: balloon seller, bargainballoons.com) = 50-60 liters.
- Expected Lift per balloon = 48 – 57 g

Actual Results:

Number of helium balloons	Robot mass readings
0	370 g
1	352 g
2	333 g
3	315 g

Observations:

- **Each balloon is only generating a Lift of 18-20 g. This is <50% of the expected value of 48-57g.**
- Possible sources of error:
  - **Impure helium** (80% helium, 20% air):
    - The tank contains minimum 80% helium (https://www.balloontime.com/contact-us/faqs/).
    - This only explains a 20% drop

  - **Inflation error**: I don't have a gauge to measure if the balloon is filled to capacity so some error is expected there.
- I don't have an explanation for the 50% difference in expected vs actual Lift

February 6th 2020

Goal: Figure out why the actual Lift generated by helium balloons is less than 50% of the expected Lift.

Steps:

- Take different type and sizes of balloons and fill them up with helium
    - Types: latex and foil
    - Sizes:
        - latex: 9"
        - foil: 18" and 35"
- Measure the net Lift generated by each type of balloons
- Try to spot any patterns

Results:

Balloon type	Net Lift
Latex 9"	3 grams
Foil 18"	2 grams
Foil 35"	18 grams

Observations

- This is very confusing. The 18" foil balloon is generating **LESS Lift** than the 9" latex balloon!
- Does the type of balloon matter?
- It's possible that the uninflated balloon itself has a mass, which is affecting my readings. I think my thrust calculation model assumes that the balloon has zero mass.

February 6th, 2020

Goal: Is the uninflated balloon mass significant enough to affect the Lift generated by the balloon?

Steps:

- Measure the mass of the different types and sizes of uninflated balloons
- Determine the balloon volume.
  - Using balloon supplier website as the balloons are irregular shaped and it's tough to measure their volume.
- Compare the uninflated mass to the expected Lift each inflated balloon can generate
- Calculate mass/Lift ratio

Results:

Balloon type	Uninflated mass of the balloon	Balloon expected volume	Expected Lift	Net Lift
Latex 9"	3 grams	7 Liters	7g	4g
Foil 18"	10 grams	11 Liters	14g	4g
Foil 35"	23 grams	24 Liters	50g	27

Observations:

- The implicit assumption about weight of the balloon not being significant enough is **WRONG**.
- Uninflated balloon mass is quite significant, in fact the net lift is just 30-50% of the expected lift if the balloon a 0g mass.
- This is a BIG CHALLENGE. At this rate, I'll need nearly 20 large balloons to balance the robot, which will make it very unwieldy…
- Need to find a balloon whose Mass/Lift ratio is not so high.

February 12th, 2020

Goal: Try 36" balloons and measure the Net Lift

Steps:

- Apply Hi float solution to the inside of the balloon so the helium doesn't escape too quickly
- Measure the uninflated mass of the balloon
- Inflate the balloon
- Measure the balloon volume, using the following steps
  - Measure the circumference of the balloon along the equator
  - Calculate the radius using the formula: Circumference = $2\pi r$.
  - Calculate the volume using $V = \frac{4}{3}\pi r^3$.
- Calculate Expected Net Lift using the formula L = V/1.04
- Measure the actual Lift using the weigh scale as done previously

Results:

Balloon	Uninflated mass of the balloon	Balloon Actual Volume	Expected Net Lift	Actual Measured Lift
1	50 grams	126 Liters	121 – 50 = 71g	60 g
2	50 grams	188 Liters	181 – 50 = 131g	120g
3	50 grams	237 Liters	228 – 50 = 178g	148 g

Observations:

- The actual measured lift is pretty close to the expected net Lift. The two values are withing 10-20% of each other. The helium purity is unknown, but according to the manufacturer, it's at least 80% pure, which is a possible source of the 10-20% difference.
- The balloon shape is not perfectly spherical, so that's another source of error, because we used the formula for a sphere's volume to calculate the volume of helium inside the balloon.
- The difference in the amount of helium inside the balloon is because I was afraid that the balloon might burst, so I wasn't able to inflate it to its maximum volume.

February, 15th, 2020

Goal: Use different batteries in the robot to reduce its total mass to reduce the amount of helium required for microgravity simulation

Steps:

- Calculate the mass of the robot: 470g
- Calculate the mass of the 9V battery and its connector: 45g
- The robot has 3 batteries:
    - Two 9V batteries connected in serial connection to power the actuator:
        - Voltage = 18 V
        - Total Mass = 90 grams.
    - One 9V battery to power the Arduino
        - Voltage = 9 V
        - Mass = 45 g
- The actuator can work with 18 V to 24 V. Replace two 9V batteries with two 12 V A23 batteries (mass 11g each).
    - Voltage = 24 V
    - Total Mass = 22 grams
- The Arduino can be powered by one 12V A23 battery also.
    - Voltage = 12V
    - Total Mass = 11 grams
- Replace the three 9V batteries with three 12 V A23 batteries

Results

Component	Old Design 9 V battery	New Design 12V A23 battery
Actuator Battery		
Voltage	18 V	24 V
Mass	90 grams	22 grams
Arduino Battery		
Voltage	9V	12V
Mass	45 grams	11 gram
Robot Mass	470 g	376g

Observations:

- Robot mass reduced by 94 grams.
- It seems that the battery life of the 12V A23 battery is lower than the 9V battery. This makes sense as it's a much smaller battery. But it results in a 20% reduction in mass, which will significantly reduce the amount of helium, so it's a good choice.

February 17th, 2020

Goal: Calculate the effective gravitational acceleration experienced by the robot when the Helium balloons are attached to it.

Steps:

- Measure the mass of the assembled robot = $M_{original}$ = 376 g
- Add the individual Lifts of the inflated Helium balloons to calculate total Lift (from the balloons inflated with helium a few days ago).
- Lift provided by 3 helium balloons = 328 grams.
- Attach the balloons to the robot.
- Measure the mass of the robot again. It should be approximately 48 grams (376 – 328) grams.
- Actual $M_{microgravity}$ = 48 grams
- Calculate the new gravitational acceleration value $g_{microgravity} = M_{microgravity} \times g_{earth} / M_{original}$
- $g_{microgravity}$ = 48 x 9.8/376 = 1.25 m/s^2 = 1/8th of Earth's gravitational acceleration.
-

Results:

Robot Mass	Lift provided by Helium balloons	Weigh scale reading after attaching helium balloons	Gravitational acceleration $g_{microgravity}$
376g	328g	48 g	1.25 m/s^2 (48 x 9.8)/376

Observations

- Even though the net Lift of the helium balloons is 48 grams less than the mass of the robot, the robot is almost floating and barely staying on the ground.
- The balloons are so big and light that even a little disturbance in the air moves them which probably creates extra lift.

February 17th, 2020

Goal: Test the robot propulsion when the Helium balloons are attached to it.

Steps:

- Attach the helium balloons (done in the previous journal entry) using a light string
- Set the impulse time to 100 milliseconds in the Arduino code
- Note the starting position of the robot
- Start the Arduino program that controls the actuator to push the regulator to release the CO2.
- Note the ending position of the robot

Results:

- The robot didn't move in a straight line as expected, instead it moved in the following way:
  - 2 feet forward
  - 2 feet to the left and started spinning counterclockwise

Observations

- **Well, that didn't work!**
- The robot layout is not correct. The nozzle is on the left side of the robot, so the thrust generated by the CO2 regulator is acting like a torque. This torque is causing the robot to spin, instead of moving in a straight line.
- The nozzle of the regulator needs to be along the centerline of the robot chassis.

February 23rd, 2020

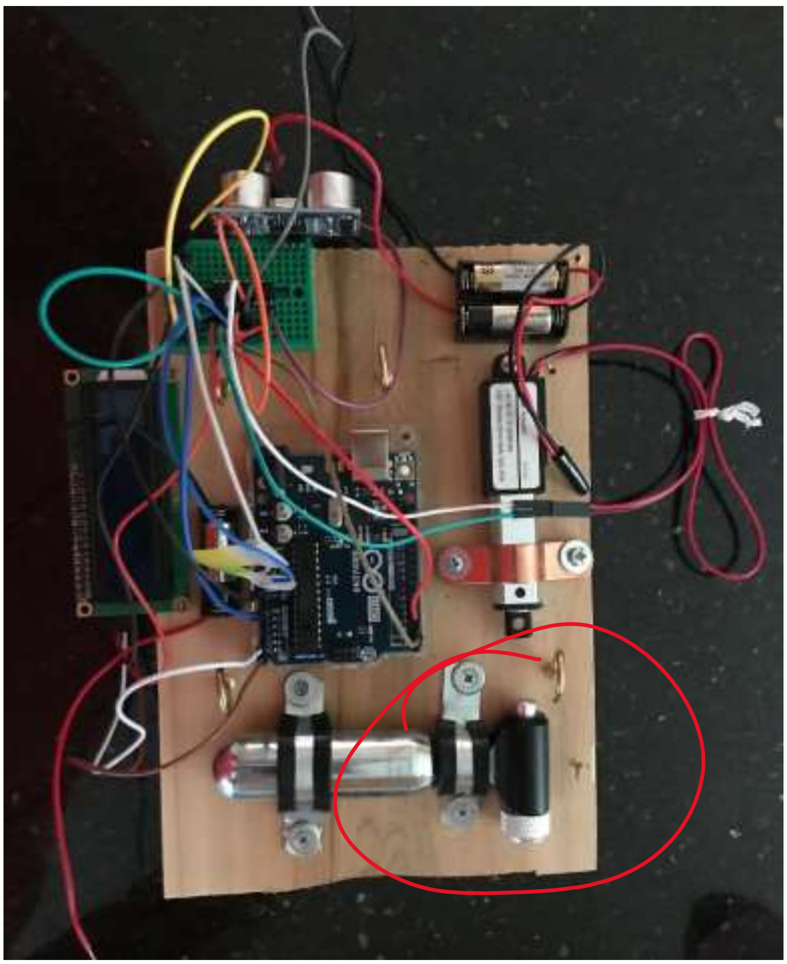
Goal: Redesign the robot layout to position the nozzle in the center of the chassis and distribute the weight evenly on the chassis

Steps:

Fix the following problems:

- The regulator exhaust is not in the middle.
- Weight is not evenly distributed

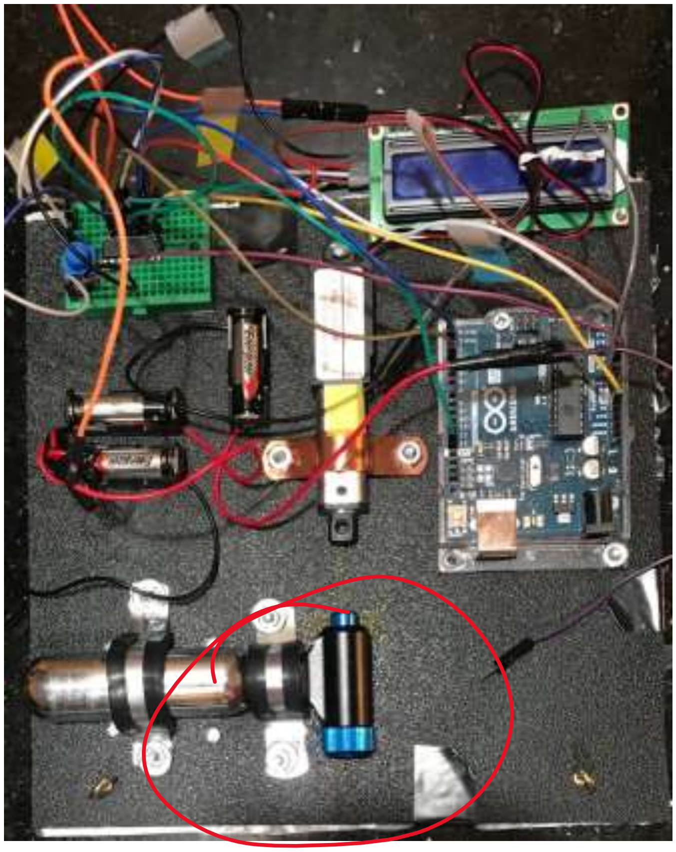
Robot prototype #2 (BEFORE):



Not Centered

Results:

Robot prototype #3 (AFTER)



Centered on the Chassis

February 25th, 2020 – March 2nd, 2020

Goal: Test the propulsion mechanism of new layout of the robot in REGULAR GRAVITY

Steps:

- Take a fresh CO2 cartridge and attach the regulator to it
- Weigh the CO2 cartridge + regulator and note down the mass
- Attach the CO2 cartridge to the robot as in the picture, tighten the brackets so the cartridge doesn't move
- Place the robot on a level floor (I used wooden floor in my home's family room)
- Start a stopwatch with 1/100th of a second accuracy (I used the stopwatch on an iPad)
- Start a video recording in slo-mo (preferably 240 fps). Make sure both the robot and the stop watch are in the same frame
- Start the robot
- Capture the motion in the video for the impulse phase and the glide phase
- Capture the following data:
    - **Duration**:
        - **Impulse duration:** Use the slo-mo video to determine the start time and end time of CO2 expulsion by noting down the stopwatch readings.
        - **Total travel time**: Use the slo-mo video to determine the start time and end time of robot movement (impulse and glide phase)
        - **Glide duration**: Subtract impulse time from total time to get the glide time.
    - **Distance**:
        - **Impulse distance**: distance traveled during the impulse phase. Use the slo-mo video to determine the distance traveled during the impulse phase.
        - **Glide distance**: subtract the impulse distance from the total distance to get the glide distance
        - **Total Distance**: use a tape measure to measure the distance traveled by the robot
    - **Thrust**:
        - **Measure actual thrust**: Use the distance formula to calculate the average acceleration. D = $\frac{1}{2} \times a \times t^2$. Rearrange to isolate acceleration and multiply it with the mass of the robot to calculate the actual thrust.
        - **Error factor:** Calculate the difference between the modeled thrust given by the rocket equation and the actual thrust.
    - **Velocity**
        - **Peak velocity**: Using the thrust calculated in the previous step to calculate the peak velocity. Peak velocity is achieved at the end of the impulse phase. Use the Impulse and momentum relationship to calculate the peak velocity as follows:
          Thrust x impulse duration = M Δv
          $\Delta v = \frac{\text{Thrust x impulse duration}}{M}$

- Fill the data in the spreadsheet as shown on the next page:

Results:

See spreadsheet.

Observations:

- The propulsion system is generating about 5.5 N of thrust.
- There is a gap in the measured thrust vs the value predicted by the model = 6.5N. The following are possible sources of error:
  - **Area measurement**: The diameter of the orifice and the exhaust were 1mm and 3mm respectively. The ruler only had an accuracy of 1mm, so this was a source of error.
  - **Lack of constant temperature**: The choked flow equation assumes constant pressure and density. Both pressure and density of CO_2 change rapidly with temperature. During experimentation, the cartridge became very cold (20°C to 4°C) during the impulse phase. The temperature drop would cause the density and pressure to be reduced and affect the mass flow rate.
  - **Accuracy of camera capturing stopwatch**: The impulse duration is approximately 0.4 – 0.5 seconds. A 240fps (frames per second) iPhone camera in slo-mo was used to capture the stop watch which had an accuracy of 1/100th of a second. The 240 fps slo-mo doesn't have enough frames to capture the 1/100th of second, so that was a source of error.
  - **Coefficient of friction**: the coefficient was never actually measured, it was taken from a reference source.
- The robot is always going left, sometimes a lot. I think it's because of the following reasons:
  - The weight is not evenly distributed
  - The regulator is not facing exactly center and perpendicular to the robot chassis
  - As the CO2 is expelled, the mass distribution changes because the cartridge weighs much less.
- Changing regulators for every run is painful as I have to take out the regulator and the cartridge. I have to remove screws and then realign everything when putting it back. A different design where the cartridge can just be screwed and unscrewed would be better.

March 3rd, 2020

Goal: Test the propulsion mechanism of the robot in MICROGRAVITY

Steps:

- Use the Helium balloons inflated previously and attach them to hooks on the robot.
- Calculate the effective gravitational acceleration value as done previously. See Journal entry on February 17th.
- The effective gravitational acceleration is: 4.6 m/s^2.
    - Mass of the robot: 433g
    - Net Lift generated by Helium balloons = 230g
    - New effective gravitational acceleration = $\frac{203\ x\ g}{433} = \ 4.6m/s^2$
- Repeat the steps as in the previous step and capture the data using the same spreadsheet

Results:

See Spreadsheet.

Observations:

- **The results are very different** from what I expected. The expectation was that in a microgravity environment, the robot would go faster and farther.
- However, the results **are exactly opposite**. The distance and the peak velocity are both significantly lower than in the higher gravity environment.
- The balloons seem to be providing a lot of drag and resistance and are almost acting like a parachute and stopping the robot very quickly.
- The formula for air resistance is:
    - Air resistance = $\frac{1}{2}c_d\rho v^2A$
    - c_d =drag coefficient = 0.5 for spheres
    - ρ = air density at 20°C = 1.2 Kg/m^3.
    - v = velocity of the robot = 3.1 m/s
    - A = cross-section area presented by the balloons = 1.11 m^2.
- Using above values, the 3 helium balloons are providing an air resistance of nearly 3.2N at a velocity of 3.1 m/s.
- It seems that the air resistance caused by the balloons is much more than the reduction in force of friction they provide.

March 4th, 2020

Goal: Figure out a way to reduce air resistance of the balloons

Hypothesis:

- Air resistance is dependent upon air density, area (cross-section area) of the balloons and the velocity of the robot. (see last page)
- The area of the helium balloon area is out of my control, so I can't change it.
- The only thing I can change is the velocity, by doing one of the following:
    - **Change Net thrust**:
        - **Decrease cartridge Thrust**: this is fixed and based on the diameter of the orifice or the cartridge pressure.
        - **Increase force of friction**: this is the only thing I can change, by increasing the coefficient of friction
    - **Reduce impulse duration**: this is hard to control. I wasn't successful getting it below 0.4 seconds consistently during the mass flow rate testing.
- **Increase coefficient of friction:** If I attach rubber "feet" to the robot, that should increase the coefficient of friction. The coefficient of friction for soft rubber on wood is: .95.

March 5th, 2020

Goal: Test the propulsion mechanism the robot in REGULAR GRAVITY and HIGH FRICTION

Steps:

- Attach rubber "shoes" to the base of the robot. I used 3 erasers
- Repeat the experiment as previously and capture all the data

Results:

See spreadsheet

Observations:

- **The rubber "shoes" are definitely providing high friction** because the peak velocity, impulse distance, glide distance and the net thrust are all significantly lower than the low friction case.

March 5th, 2020

Goal: Test the propulsion mechanism the robot in MICROGRAVITY and HIGH FRICTION

Steps:

- Attach rubber "shoes" to the base of the robot. I used 3 erasers
- Attach helium balloons to the robot
- Repeat the experiment as previously and capture all the data

Results:

See spreadsheet

Observations:

- There still seems to be significant air drag, but it's definitely better than the low friction case.
- The drag doesn't seem to impact the impulse phase as much as it's doing the glide phase. The robot stops in the glide phase very quickly. This is probably because of the high friction and the air drag