Robot Propulsion in an Asteroid's Microgravity Environment

Parth Chaudhry
Algonquin Regional High School
Northborough, MA

1 TABLE OF CONTENTS

2 ABSTRACT

Traditional robots that move using wheels or legs won't work in an asteroid's microgravity environment (1/100th to 1/100,000th that of Earth) because of lack of friction and low escape velocity. The goal of this project was to build a robot propulsion system that can work in microgravity by using cold gas (CG) propulsion. Another goal was to simulate microgravity using Helium balloons and then test the robot propulsion system in microgravity.

A robot propulsion system using cold gas propulsion was successfully built and tested using commonly available materials, including a 16g high pressure CO_2 cartridge (853 psi, $1.50/each), a regulator (nozzle), a linear actuator and an Arduino controller. The mass flow rate and exhaust velocity of the system were calculated using the choked flow equation and calculators on the NASA GRC site. The mass flow rate was calculated to be: 0.012Kg/s and the exhaust velocity was: 556.8 m/s. Using these values and the rocket equation it was calculated that the robot would generate a thrust of 6.5N. During testing, the robot generated an actual thrust of 5.6N with an impulse duration of 0.5 seconds. The main sources of error were measurement errors due to lack of accurate measuring devices and quality of the CO_2 cartridge.

A microgravity system was also simulated using Helium balloons which reduced gravitational acceleration to as low as 1.25 m/s^2 (1/8th that of Earth). While even lower values of gravitational acceleration were possible, the large size (diameter 28"+) and lightness of the balloons made them very prone to air disturbance creating unintended thrust vectors.

Robot propulsion was tested in both regular gravity and microgravity environments. The robot performed predictably in regular gravity and the measurements were in line with the model. However, in microgravity the results were mixed. The high speed of the robot (> 3m/s) caused the Helium balloons to generate significant air drag which significantly affected the results, especially when the coefficient of friction between the robot and the surface was low. Increasing the coefficient of friction reduced the effect of air drag and the robot behaved more predictably, i.e. it had higher speed and traveled a longer distance in microgravity vs regular gravity.

Overall, the results demonstrated that cold gas propulsion can be used for robot propulsion in microgravity with predictable results, but Helium balloons are not suited for use with high thrust propulsion like cold gas propulsion due to the effects of air drag. Low thrust propulsion mechanisms like hopping and ion thrust engines may be more suitable for Helium balloon simulated microgravity.

Detailed results of the experiment including all data can be downloaded here: https://astmine.com/mg-robot.

3 INTRODUCTION

Asteroid mining is very important for humans to become a multi-planet species. A lot of resources are needed for space colonization and it's too expensive to take them all from Earth (it costs $10,000/Kg to ship to LEO). Asteroids are expected to be rich in resources like water and metals, which can help us. Asteroid mining is not possible today, but it should become possible in the next 5-10 years as the new technologies develop.

One of the technologies that needs development is robot propulsion in a micro- or zero- gravity environment. Traditional robots designed for moving in Earth's gravity can't function in a microgravity environment of an asteroid or a zero-gravity environment of the International Space Station. Newer methods of robot propulsion are needed which can allow robots to function in both micro- and zero-gravity environments.

3.1 MICROGRAVITY PROPULSION CHALLENGES

3.1.1 Microgravity Environment

The force of gravity on an asteroid is really low. For example, the gravitational acceleration on the asteroid Ryugu is: 0.11~0.15 mm/s^2, which is about eighty thousandths (~ 1/80000th) that of Earth (Hayabusa2 Mission Site, n.d.). Due to Microgravity, escape velocity on an Asteroid is also really low, on the Asteroid Ryugu it is 38cm/s (Planetary Society, n.d.), which is 1/30,000 of Earth's escape velocity 11.2km/s. This is a big problem for two reasons:

1. **Wheels won't work because of lack of friction**:
2. **Newton's 3rd law and low escape velocity**

3.1.2 Wheels won't work

Moving about on the Asteroid is a challenge because of microgravity. Wheel based rovers like Curiosity won't work in a microgravity environment. This is because the force of friction on the asteroid is really small (1/80000th of that on Earth) which will cause the wheels of the rover to just spin in place. The Japanese mission Hayabusa, which went to Ryugu, created a rover which moves by hopping instead (Hayabusa mission site, n.d.).

3.1.3 Newton's 3rd law and low escape velocity:

Any downward force applied on the Asteroid by the prospecting robot will result in an equal and opposite force on the robot (Newton's 3rd law). In a microgravity environment of an Asteroid, this force can be enough to send the robot flying off the Asteroid. So, care needs to be taken to avoid flying off the asteroid by mistake.

4 GOAL

This experiment has the following goals:

Goals:

1. **Build a robot propulsion system** that can move around in a microgravity environment using Cold gas propulsion.
    a. The robot should be able to generate a thrust of at least 1N.
    b. The robot should be able to vary the impulse duration.
    c. The robot should have a mass less than 0.5 Kg (otherwise too much Helium would be required to generate microgravity)
2. **Simulate a microgravity system** using helium balloons
    a. Achieve gravitational acceleration of at least 1/10th that of Earth.
    b. The system should be able to vary the effective gravitational acceleration by varying the amount of helium. The amount of helium will be varied manually and not automatically.
3. **Test the robot propulsion in the microgravity environment** of Helium balloons and regular gravity and compare the robot performance by measuring the following:
    a. Net thrust experienced by the robot
    b. Peak velocity achieved by the robot
    c. Impulse distance
    d. Glide distance

5 Experiment Design

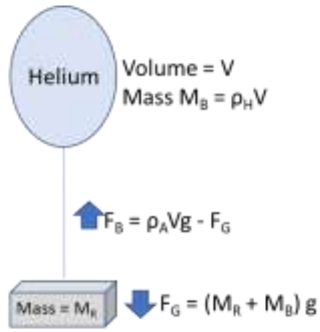
The experiment had the following major parts:

I. Build and test a system for microgravity simulation
II. Build a system for Robot Propulsion
    1. Cold gas propulsion system
    2. Arduino Controller
III. Test Robot propulsion in the following scenarios:
    1. Standalone to measure generated thrust vs expected thrust
    2. Low friction coefficient environment:
        a) In regular gravity
        b) In microgravity
    3. High friction coefficient environment
        a) In regular gravity
        b) In microgravity

5.1 Microgravity Simulation

5.1.1 Background

The experiment simulated Microgravity using helium balloons. Helium is lighter than air and a helium balloon exerts a net upward force which is proportional to the volume of the balloon. The following picture shows the force diagram.



If the upward force F_B is nearly equal to the downward force of gravity F_G, we can create a microgravity environment.

For a microgravity environment $F_B \approx F_G$

$\rho_A Vg \approx (M_R + \rho_H V)\ g$

The volume V of the balloon can be calculated in terms of the mass of the payload M_R.

$V = M_R/(\rho_A - \rho_H)$

Density of air (ρ_A) at 20° C and 1 Atm pressure = 1.204 g/L (Engineering ToolBox, n.d.)

Density of Helium(ρ_H) at 20° C and 1 Atm pressure = 0.1634 g/L (Engineering ToolBox, n.d.)

$V = M_R/(1.1204 – 0.1634)$ L

$V = .961 \times M_R$ Liters, where the mass is in grams.

Volume of a Helium balloon needed to approximately equal the force of gravity on an object of Mass M_R grams on Earth at 20° C and 1 Atm pressure = .961 M_R Liters.

5.1.2 Experiment Setup

There are two components to the setup:

- Helium balloons:
  - The setup used 36" latex balloons. The balloons were coated with Hi Float solution to prevent the Helium from leaking too quickly.
  - Each uninflated balloon coated with the Hi Float solution had a mass of 50g.
  - The "Lift" generated by the Helium in the balloon is reduced by the mass of the uninflated balloon.
- Helium
  - The setup used Helium available from the company Balloon Time, which is available in most stores. This Helium is only 80-90% pure and the rest is air. Pure Helium is very hard to get due to a worldwide shortage of Helium. This reduces the net "Lift".

5.1.3 Experiment Steps

1. Measure the mass of the robot using a weigh scale with at least 1g accuracy. Let's say it is $M_{original}$ grams.
2. Measure the mass of the uninflated balloon (36" size, coated with Hi-Float).

3. Fill the balloon with helium and attach it to the robot.
4. Measure the volume of the Balloon (assumption made of a perfect sphere).
5. Calculate the "expected Lift" using the formula in the previous section. Subtract the mass of the uninflated balloon.
6. Attach the balloon to the robot and measure the mass of the robot again, it should be less than in the first step. Let's say this mass is: $M_{microgravity}$
7. Calculate the difference vs the 1st step. Let's say it's reduced by x grams. This is the "actual Lift" generated by the balloon.
8. Compare the "actual Lift" with the "expected Lift".
9. Calculate the net gravitational acceleration as a result of the Lift. The formula is: $g_{microgravity} = M_{microgravity} \times g_{earth} / M_{original}$

5.2 Robot Propulsion

5.2.1 Cold gas propulsion

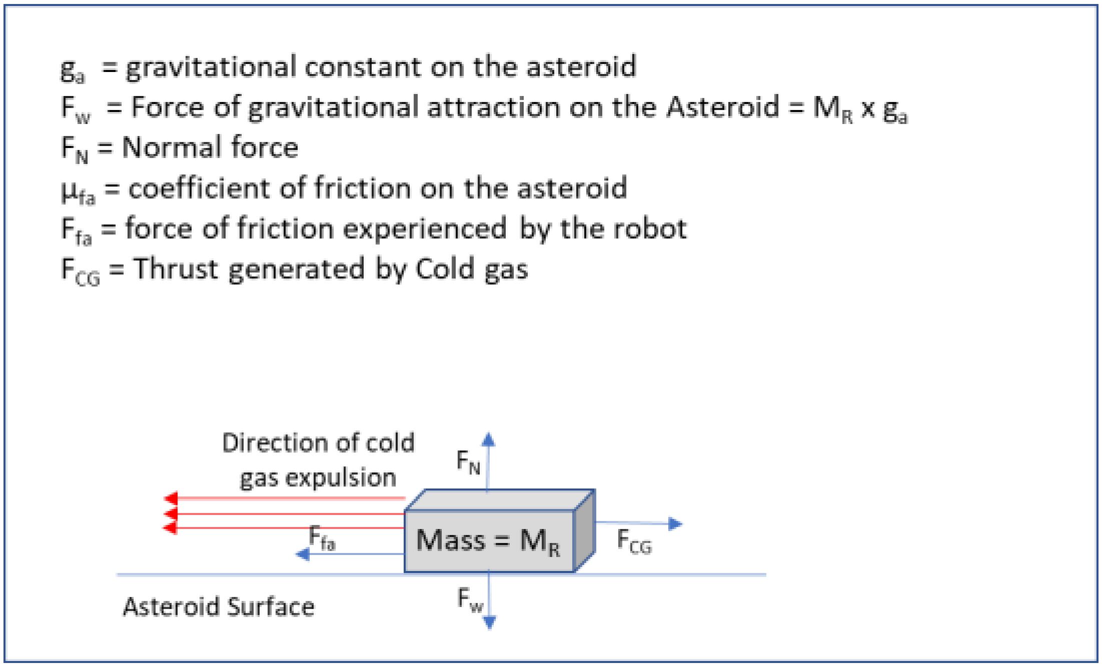
Cold Gas (CG) propulsion is based on Newton's 3rd law and conservation of momentum to achieve propulsion. A gas under high pressure is expelled, which creates a thrust in the opposite direction. The thrust depends on the molecular mass of the gas and the pressure at which it is stored. The robot will use CO_2 as the cold gas, because it is available cheaply. The gas will be expelled from a regulator with a small orifice.

There are 2 methods to move on a surface using CG propulsion:

1. **Slide**: In this method, the CG propulsion generates enough forward thrust to overcome the force of friction experienced by the robot on the surface of the asteroid.
2. **Fly**: In this method, the robot is not in contact with the surface and is hovering. It uses the forward thrust generated by the CG propulsion system to "fly".

This experiment will use method 1.

5.2.1.1 Cold Gas Propulsion – Slide



For the robot to be able to move, the thrust generated by the CG propulsion needs to be greater than the force of friction, i.e. $F_{CG} > F_{fa}$.

$F_{fa} = \mu_{fa}$ x M_R x g_a

For the robot to move,

FCG > μ_{fa} x M_R x g_a

5.2.1.2 System Parts

The cold gas propulsion system consists of:

- A tank containing pressurized CO_2
- A regulator to release the CO_2 via an orifice
- An actuator to control the flow of CO_2 via the regulator to generate the required impulse

5.2.1.2.1 Tank

The robot used CO_2 as the cold gas. To keep costs low, the robot used a commercially available CO_2 cylinder cartridge (16g, $1.50/each), available on Amazon. The initial pressure in the CO_2 cartridge is approximately 852.8psi at 70°F. Here's a picture of the cartridge (Amazon, n.d.):

5.2.1.2.2 Regulator

The robot used a commercially available, inexpensive regulator ($15 on Amazon) to control the flow of CO_2 through a small orifice. The regulator has a small button, which when pushed releases CO_2. The button requires a minimum of 34 N of force (measured experimentally) to be applied. Here's a picture of the regulator (Amazon, n.d.):

5.2.1.2.3 Actuator to push the button on the regulator

The robot used a linear actuator ($30 on Amazon) (USLICCX actuator, n.d.) to push the button to generate the required impulse. The actuator generates a thrust of up to 64N, which is sufficient to press the regulator button. Here's a picture of the actuator (Amazon, n.d.):

5.2.1.3 Thrust generated by the system

The thrust generated by cold gas propulsion is given by the rocket equation (Rocket Thrust Summary, n.d.):

- $\dot{m} \times V_e + (P_e - P_o) \times A_e$

Where:

- $\dot{m}$ (m dot) is the mass flow rate
- V_e is the exhaust velocity of the propellant (the cold gas)
- P_e = pressure in exhaust area of the regulator
- P_o = ambient pressure = 101325 N/m^2
- A_e = area of the exhaust area of the regulator = 7.07 x 10^{-6} m^2

5.2.1.3.1 Calculating mass flow rate

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 (NASA Glenn Research Center, n.d.) and (Choked Flow Equation, n.d.). 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 850 psi, 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. The experiment used a value of 0.7
- A = area of the orifice the propellant comes out of. The diameter of the orifice was measured to be 1mm. The ruler that was used had an accuracy of only 1mm. The area = 7.9 x 10^{-7} m^2
- ρ_0 = real gas density of the gas at pressure P_0 and Temperature T_0. At 20 oC and 57 atm the density = 192 Kg/m3. (Penn State Energy Institute, n.d.)
- P_0 = pressure of the gas in the tank: 5.77 x 10^6 N/m^2. (Penn State Energy Institute, n.d.)
- γ = specific heat ratio of the gas (= 1.3 for CO_2) (Choked Flow Equation, n.d.)

5.2.1.3.2 Calculating exhaust velocity

Exhaust velocity $V_e = M_e\sqrt{k * R * Te}$ (Rocket Thrust Summary, n.d.)

where

M_e = Mach number

k = specific heat ratio of the gas (= 1.3 for CO_2)

R = specific gas constant for CO2 (188.9 J-Kg^{-1}-K^{-1}). Universal gas constant divided by molar mass of CO_2.

T_e = gas temperature in exhaust area

5.2.1.3.3 Expected thrust

The area ratio $A_e/A = 9$.

The following values were obtained using the calculator on the NASA GRC website (Mach number and Area Ratio, n.d.):

- Mach number: 3.489
- P_e = 64108 N/m^2
- T_e = 103.7 K (this is the temperature of the gas in the exhaust area)

Using the inputs specified above, the following was calculated:

- Mass flow rate = 0.012Kg/s
- Exhaust velocity = 556.8 m/s

By plugging these values into the rocket equation, the expected thrust was obtained to be: 6.4 N.

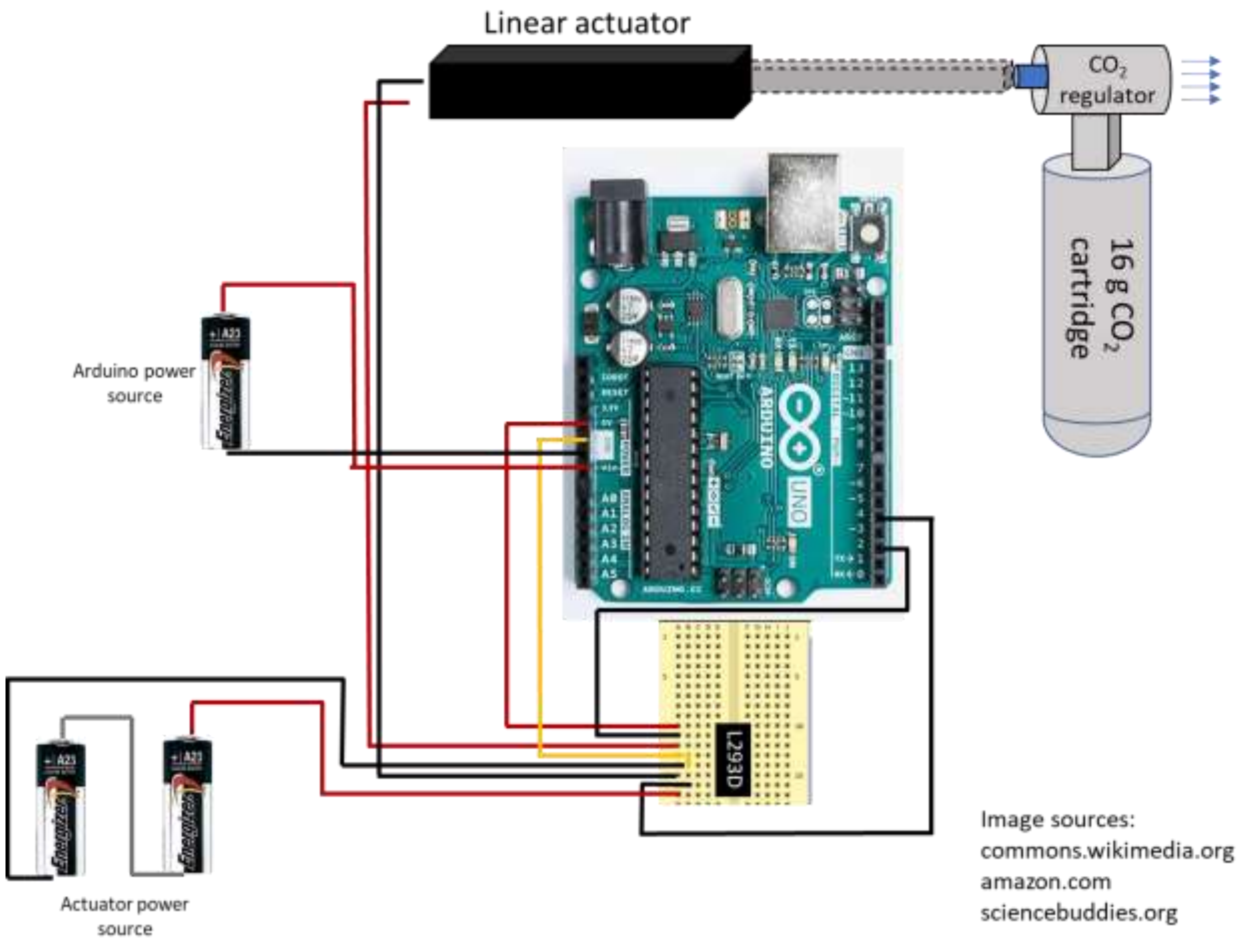
5.2.2 Arduino Control

The cold gas propulsion system was controlled using an Arduino Uno controller. There are two parts to the Arduino control:

1. The Arduino circuit that connects the various components.
2. The source code to control the components

5.2.2.1 The Arduino Circuit

The Arduino circuit picture is shown below:



The actual robot also used an LCD screen and a potentiometer, but those are optional and are omitted for clarity.

5.2.2.2 The Source Code

The source code can be download here: https://astmine.com/mg-robot

5.2.3 Conducting the Experiment

Following are miscellaneous items and details:

- A 240 fps camera: an iPhone 7s plus camera which supports slo-mo video of 240 frames per second (fps) was used. This was very useful to measure time intervals that were less than 1 second.
- A stopwatch with 1/100th of a second accuracy: an iPhone/iPad stopwatch was used.
- A digital weigh scale with an accuracy of 1g was used to measure mass.
- A tape measure with an accuracy of 1/16th of an inch was used to measure distance.
- Robot was placed on a wooden floor.
- The Robot was tested with two different bases under the chassis:
    - Plastic: The coefficient of friction used was: 0.4. Plastic on wood. (Univ of Florida, n.d.)

- Rubber "shoes": The coefficient of friction used was 0.7. Hard rubber on wood. (Univ of Florida, n.d.)

6 Experiment Results

6.1 Microgravity Simulation Using Helium Balloons

6.1.1 Individual balloon Lift

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

6.1.2 Combined Lift of 3 balloons.

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

Notes:

- Even though the net Lift of the helium balloons was 48 grams less than the mass of the robot, the robot was nearly floating and barely staying on the ground.
- The balloons are so big (diameter of 28" and up) and so light that even a little disturbance in the air moved them creating extra lift for the robot.

6.2 Robot Thrust Measurement in Regular Gravity

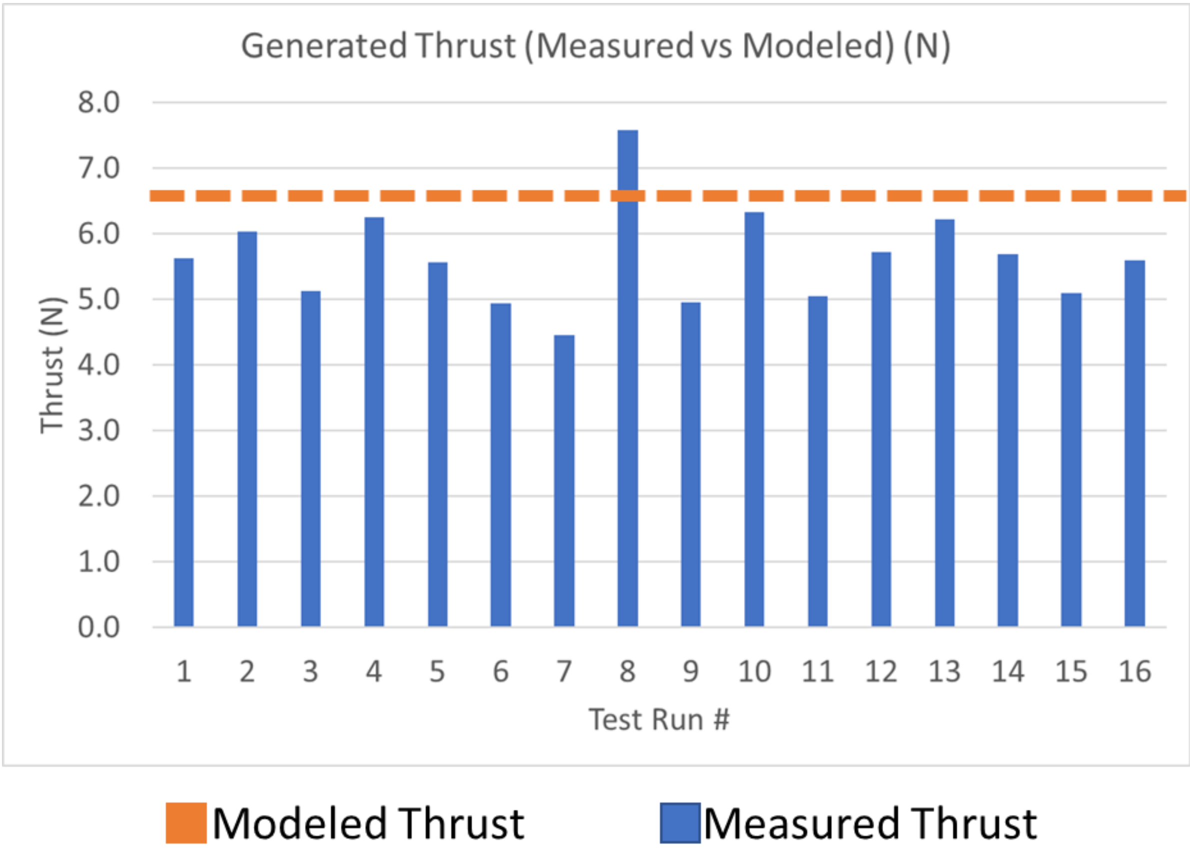
6.2.1 Steps:

- The robot was placed on a wooden floor in a regular gravity environment. The robot was started with an impulse duration set to approximately 0.4 seconds.
- The following results were measured. A detailed spreadsheet can be downloaded here: https://astmine.com/mg-robot

6.2.2 Results:

- Expected Thrust (predicted by rocket equation) = 6.5N

Results of Robot Propulsion:



- There are 3 types of thrust values:
  - **Modeled Thrust** = thrust calculated using the rocket equation = $\dot{m}$ x V_e + (P_e-P_o)A_e
  - **Measured Net Thrust** = thrust actually experienced by the robot during the impulse phase.
  - **Measured Thrust** = Measured Net Thrust + Force of Friction. This is also known as Applied Thrust. This is the thrust that was actually generated by the propulsion system.
- Since the actual impulse distance (d) and the impulse duration (t) were measured, Measured Net Thrust can be calculated using the formula:
  - F = m*2d/(t^2), where m = mass of the robot.

  This formula can be gotten by rearranging the formula: d= v_0t + ½ at^2. Since initial velocity v_0 = 0 and a = F/m, the formula can be rearranged as above.

- Observations:
  - The average thrust was measured to be: 5.6 N
  - This is 14% less than the modeled value of 6.5 N.

6.3 Robot Propulsion in Regular and Microgravity

6.3.1 Low Friction Coefficient Environment

6.3.1.1 Regular Gravity

- Robot mass: 0.433 Kg
- **Gravitational acceleration: 9.8 m/s^2 (Regular gravity)**
- Coefficient of friction: 0.4
- Force of friction: 1.7 N

Results of Robot Propulsion:

Run #	Impulse duration (s)	Impulse Distance (m)	Measured Net Thrust (N)	Peak Velocity (m/s)	Glide Distance (m)
1	0.42	0.8	3.9	3.8	2.02
2	0.4	0.8	4.3	4.0	2.3
3	0.34	0.5	3.4	2.7	1.22
4	0.39	0.8	4.6	4.1	2.17
5	0.37	0.7	3.9	3.3	1.57

6.3.1.2 MicroGravity

- Robot mass: 0.433 Kg
- **Gravitational acceleration: 4.6 m/s^2 (Microgravity)**
- Coefficient of friction: 0.4
- Force of friction: 0.8 N

Results of Robot Propulsion:

Run #	Impulse duration (s)	Impulse Distance (m)	Measured Net Thrust (N)	Peak Velocity (m/s)	Glide Distance (m)
1	0.33	0.51	4.1	3.1	1.09
2	0.37	0.6	3.6	3.1	1.13
3	0.21	0.3	6.7	3.3	0.8

Notes:

- The experiment didn't go as planned, because of the following:
  - The helium balloons provided too much air resistance.
  - The robot moved much faster in the beginning, but the balloons stayed back, causing the robot to lift up the ground and then fall back.
  - Upon falling down, the actuator got interrupted, which affected the impulse duration. The impulse times were smaller than in the regular gravity case.

- Air resistance was a significant factor. At a peak speed of 3.1 m/s, the air resistance would've been:
  - 3.2 N
  - Air resistance = ½ C_d x ρ x A x v^2
  - Calculations below.

Air resistance	3.2 N			
Drag coefficient	0.5	Drag coefficient for a sphere: https://www.engineeringtoolbox.com/drag-coefficient-d_627.html		
Density of air (20° C)	1.2 Kg/m^3			
Velocity (m/s)	3.1 m/s			
Total Area (sq m)	1.11 sq m	**Circumference**	**Radius**	
Balloon 1	0.32 sq m	2.0m	0.32m	
Balloon 2	0.47 sq m	2.4m	0.39m	
Balloon 3	0.32 sq m	2.0m	0.32m	

6.3.2 High Friction Coefficient Environment

6.3.2.1 Regular Gravity

- Robot mass: 0.494 Kg
- **Gravitational acceleration: 9.8 m/s^2 (Regular gravity)**
- Coefficient of friction: 0.7
- Force of friction: 3.4 N

Results of Robot Propulsion:

Run #	Impulse duration (s)	Impulse Distance (m)	Measured Net Thrust (N)	Peak Velocity (m/s)	Glide Distance (m)
1	0.43	0.3	1.6	1.4	0.13
2	0.48	0.7	2.9	2.9	0.91
3	0.5	0.4	1.7	1.7	0.47
4	0.56	0.7	2.3	2.6	0.79

6.3.2.2 MicroGravity

- Robot mass: 0.494 Kg
- **Gravitational acceleration: 5.4 m/s^2 (Microgravity)**
- Coefficient of friction: 0.7
- Force of friction: 1.9 N

Results of Robot Propulsion:

Run #	Impulse duration (s)	Impulse Distance (m)	Measured Net Thrust (N)	Peak Velocity (m/s)	Glide Distance (m)
1	.45	0.9	4.3	4.0	0.58

2	.43	0.7	3.8	3.3	0.66
3	.46	0.7	3.2	3.0	0.64
4	.48	0.9	3.7	3.6	0.69

7 DISCUSSION

7.1 MICROGRAVITY SIMULATION

Key observations:

1. Using Helium balloons a microgravity environment was successfully created and an effective gravitational acceleration of 1.25 m/s2 was achieved, which is 12.7% of Earth's gravity.
2. However, due to the large size and lightness of the Helium balloons, challenges were experienced using them:
    a. Air resistance: Air resistance was a significant factor because the thrust generated by cold gas propulsion causes a high velocity for the robot, which caused a lot of air resistance, up to 3.2N.
    b. Prone to air disturbance: because the balloons are so light that they move at the slightest disturbance and generate unintended thrust.
3. Reducing the effective thrust by increasing the friction coefficient, reduced the effect of air resistance, though not completely.
4. Helium balloons may be suitable for low thrust propulsion mechanisms like hopping and ion thrust engines.

7.2 ROBOT THRUST MEASUREMENT IN REGULAR GRAVITY

Key observations:

1. The robot was able to generate an average thrust of 5.6 N with an impulse duration of 0.3 – 0.5 seconds.
2. The measured thrust is 14% less than the modeled value of 6.5 N. Sources of error include:
    a. **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.
    b. **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^{o}C to 4^{o}C) during the impulse phase. The temperature drop would cause the density and pressure to be reduced and affect the mass flow rate.
    c. **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.
    d. **Coefficient of friction**: the coefficient was never actually measured, it was taken from a reference source.

7.3 Robot Propulsion in Regular and Microgravity

There is significant difference in the robot performance in microgravity in low vs high friction coefficient environment.

7.3.1 Low Friction Coefficient Environment:

1. The robot behaves predictably in the regular gravity environment, achieving a peak velocity between 3-4 m/s and gliding for a distance of 1.5 – 2.2 m.
2. In microgravity, the results are highly variable due to the effect of air resistance caused by high speed of the robot, which causes the robot to almost fly up and then land.
3. The air resistance was calculated to have a peak value of >3N, which is much more than any reduction in friction provided by the balloons by lowering gravity.

7.3.2 High Friction Coefficient Environment

1. The robot behaves predictably in the regular gravity environment, achieving a peak velocity of 1.7 – 2.9 m/s and gliding for a distance of 0.5 – 0.9 m.
2. In microgravity, the robot achieves a peak velocity of 3-4m/s demonstrating that the helium balloons reduce the force of friction by reducing the gravitational acceleration.
3. While the results in microgravity are more predictable, the air resistance provided by the balloons is still a significant factor.

8 Conclusions

8.1 Robot Propulsion Using Cold Gas Propulsion

1. Cold gas propulsion is an effective method for robot propulsion in a microgravity environment.
2. Quality of CO_2 tank and highly accurate orifice size measurement are important to ensure that predicted results match actual results.

8.2 Microgravity Simulation

1. Helium balloons are effective for creating a microgravity environment, provided there is no high-speed motion (> 1m/s).

8.3 Robot Propulsion in Helium Balloon Microgravity

1. Cold gas propulsion system can be tested in a microgravity environment, provided the speed of the system is low (< 1 m/s). Increasing the coefficient of friction is a possible way to reduce speed.
2. Lower thrust systems like hopping and ion thrust engines may be more suitable for testing with Helium balloons.

9 ACKNOWLEDGEMENTS

- Mrs Catherine Burchat: my Chemistry teacher for reviewing my work and for her guidance.
- Mr Puneesh Chaudhry: my dad, for helping me research and for being a sounding board.

10 BIBLIOGRAPHY

(n.d.). Retrieved from Planetary Society: https://www.planetary.org/blogs/jason-davis/hayabusa2-touchdown-recap.html

(n.d.). Retrieved from Hayabusa2 Mission Site: http://www.hayabusa2.jaxa.jp/en/topics/20181225e_AstroDynamics/

(n.d.). Retrieved from Engineering ToolBox: https://www.engineeringtoolbox.com/air-density-specific-weight-d_600.html

(n.d.). Retrieved from Engineering ToolBox: https://www.engineeringtoolbox.com/helium-density-specific-weight-temperature-pressure-d_2090.html

(n.d.). Retrieved from Amazon: www.amazon.com

(n.d.). Retrieved from Amazon: www.amazon.com

(n.d.). Retrieved from NASA Glenn Research Center: https://www.grc.nasa.gov/WWW/k-12/airplane/mflchk.html

(n.d.). Retrieved from Penn State Energy Institute: http://www.energy.psu.edu/tools/CO2-EOS/index.php

(n.d.). Retrieved from Univ of Florida: https://mae.ufl.edu/designlab/Class%20Projects/Background%20Information/Friction%20coefficients.htm

Choked Flow Equation. (n.d.). Retrieved from https://en.wikipedia.org/wiki/Choked_flow#Mass_flow_rate_of_a_gas_at_choked_conditions

Fine-Civil-Engineering-Software. (n.d.). Retrieved from https://www.finesoftware.eu/help/geo5/en/table-of-ultimate-friction-factors-for-dissimilar-materials-01/

Hayabusa mission site. (n.d.). Retrieved from http://www.hayabusa2.jaxa.jp/en/topics/20181225e_AstroDynamics/

Mach number and Area Ratio. (n.d.). Retrieved from https://www.grc.nasa.gov/WWW/K-12/airplane/astar.html

Rocket Thrust Summary. (n.d.). Retrieved from NASA GRC: https://www.grc.nasa.gov/WWW/K-12/rocket/rktthsum.html

USLICCX actuator. (n.d.). Retrieved from https://www.amazon.com/gp/product/B07X3Z68GV/ref=ppx_yo_dt_b_search_asin_title?ie=UTF8&psc=1

Wikipedia. (n.d.). Retrieved from https://en.wikipedia.org/wiki/Choked_flow#Mass_flow_rate_of_a_gas_at_choked_conditions