Indian Institute of Technology, Kanpur

Undergraduate Project
Project Report

3 Degrees of Freedom Spacecraft Simulator for Close-Proximity Operations

Submitted by
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CERTIFICATE

This is to certify that the project titled "**3 Degrees of Freedom Spacecraft Simulator for Close-Proximity Operations**" submitted by **S.Saikrishna**(200827) is a bonafide record of the work done by him under my guidance and supervision

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I. Acknowledgment

First and foremost, I am grateful to the institute IIT Kanpur, and my Project Supervisor Dr. Dipak Kumar Giri and Mentor Nitika Jaggi for giving me the opportunity to work under their guidance. I am deeply indebted to my professor and my mentor for encouraging me to work on new domains, which brought me outside my comfort zone. I am thankful to them for guiding and mentoring by project, whenever I was stuck and for giving me a chance to explore my abilities. I am extremely thankful to the Department of Aerospace Engineering, IIT Kanpur for providing me an environment, that helped me develop an interest in research and further studies. This project would have been impossible without the constant support and inspiration of my parents, who had faith in me, much more than I could have. They guided and motivated me throughout, helping me go through difficult days and inspiring me to work harder.

II. Introduction

A 3 Degrees of Freedom (3-DoF) spacecraft simulator is a system that simulates the movement of a spacecraft with three degrees of freedom - translation along two axes and rotation about one axis, which is simply 2-D motion. Designed for the study of close-proximity operations in which accurate spacecraft attitude control is crucial, such as docking or rendezvous. It can be utilised for R&D in spacecraft operations. By applying a realistic simulation environment, the 3-DoF simulator permits the testing and refinement of procedures/techniques, thereby enhancing the safety/efficiency of space missions.

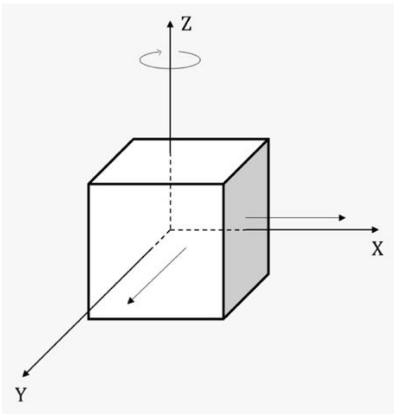


Fig. Schematic of 3 DOF Setup

This setup consists of many subsystems such as Reaction Wheel Subsystem, Thruster Subsystem, Magnetic Levitation Subsystem, etc. In this report we will discuss about the theoretical modelling of the Reaction Wheel Subsystem and Thruster Subsystem using Simulink and Simscape software.

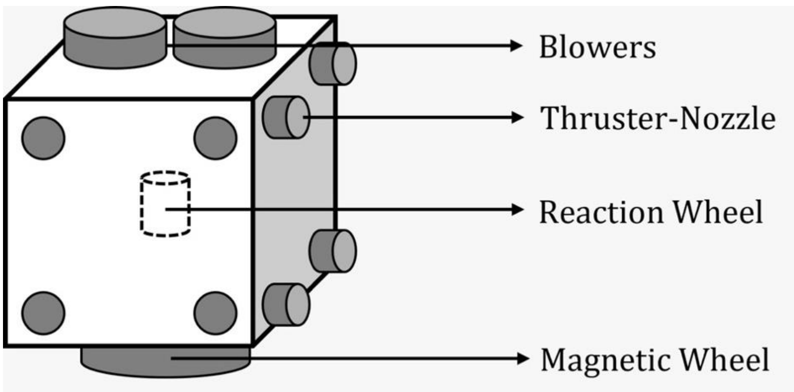


Fig. Schematic of the Spacecraft

III. Reaction Wheel Subsystem

A. Overview

Reaction/momentum wheels are flywheels utilized on spacecraft for attitude control authority and stability. By adding or subtracting energy from the flywheel, torque is applied to a specific axis of the spacecraft, causing it to rotate in response. A single spacecraft axis is stabilized by sustaining flywheel rotation. A model of the reaction wheel subsystem used in the 3 Degrees of Freedom (DOF) spacecraft simulator is created using the Simscape software.

Fig. Reaction Wheel model in PLA attached to Motor

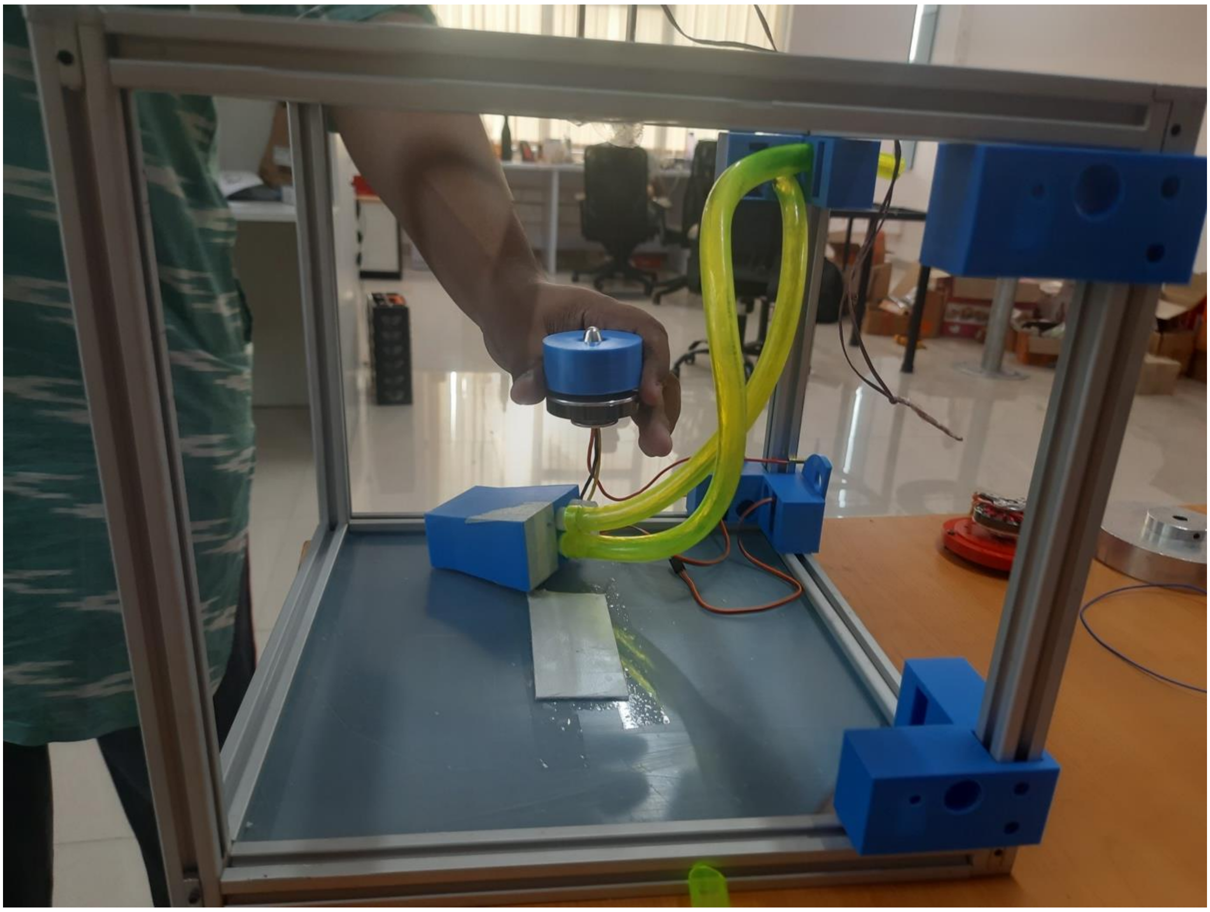


Fig. Position of reaction wheel in the 3 DoF Spacecraft simulator

B. Modeling of Reaction Wheel Subsystem in Simscape

The reaction wheel subsystem consists of a flywheel attached to a DC motor through the shaft and are at a constant distance from each other. The flywheel was created through Autodesk Fusion 360 software. The specifications of the flywheel and the DC motor are given below.

Specifications of Flywheel:

1. Material: PLA (Polylactic Acid)
2. Diameter: 30 cm
3. Density: 1240 kg/m^3
4. Mass: 0.352 Kg
5. Center of mass position (WRT origin defined in the CAD model): [1.83709e-07, 1.66408e-06, 0.00803719] m.
6. Moments of inertia: [0.000502815, 0.000502815, 0.000990484] kg*m^2
7. Products of inertia: [-1.33375e-12, -3.57932e-10, 1.05075e-13] kg*m^2

Specifications of the DC Motor:

1. Model: Rhino Planetary Geared Quad Encoder 500RPM 6Kgcm DC Servo Motor
2. Operating Voltage: 12V DC
3. Motor speed at output shaft: 450 RPM
4. Stall torque: 22Kgcm
5. Rated Torque: 6Kgcm.
6. Weight: 300gm
7. Diameter of shaft: 6mm

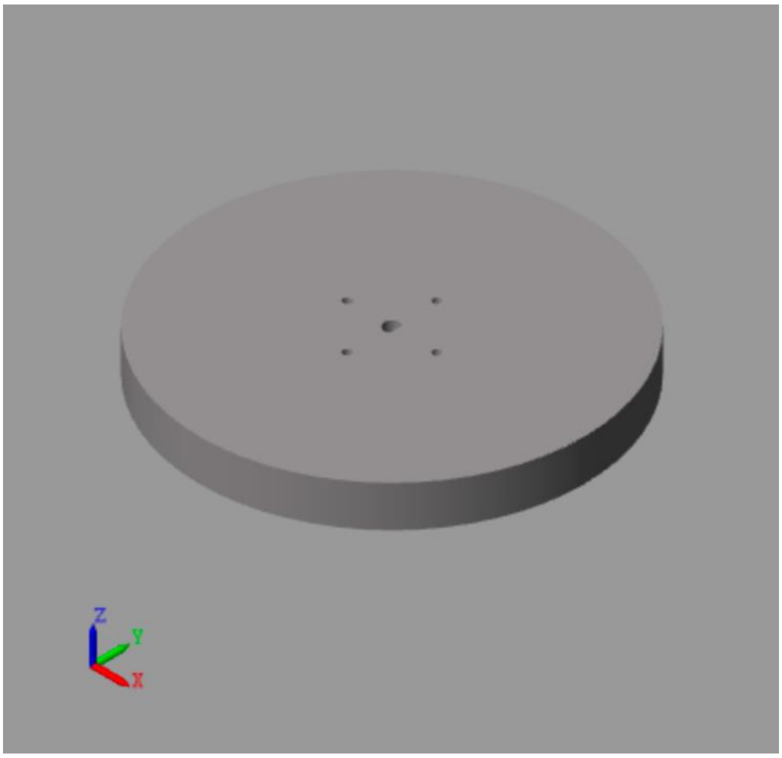


Fig. 3 Flywheel used in the model.

Fig. 4 DC Motor used in the model.

The reaction wheel subsystem modelled in Simscape consists of voltage as the input and the angular velocity as the output. For the voltage input a constant potential difference block was connected. The subsystem consists of a DC motor subsystem, a Rigid Transform block and the File Solid block. The STEP file of the CAD model was imported into this block to define the geometry and the density was specified to get the values of the center of mass, the moment of inertia and products of inertia matrices.

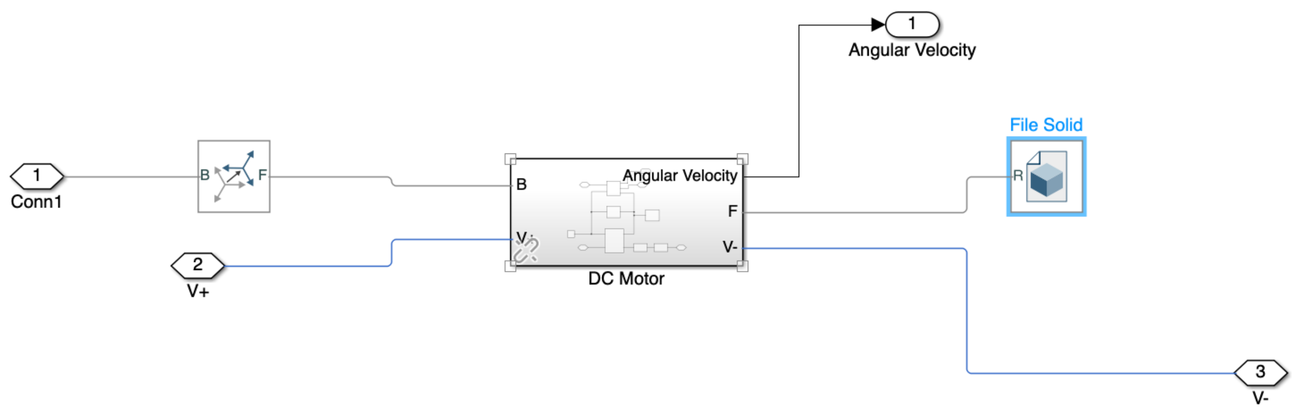


Fig. Simscape model of the Reaction Wheel Subsystem

The DC motor subsystem can be found in the Simscape -> Multibody -> DC motor. It consists of a rotational inertia block, in which the moment of inertia of the DC motor is specified, a rotational friction block, a rotational multibody block, a rotational electromechanical converter in which the constant of proportionality= 0.0266666666666666 V/rpm. It also has an inductance and resistance for the DC motor.

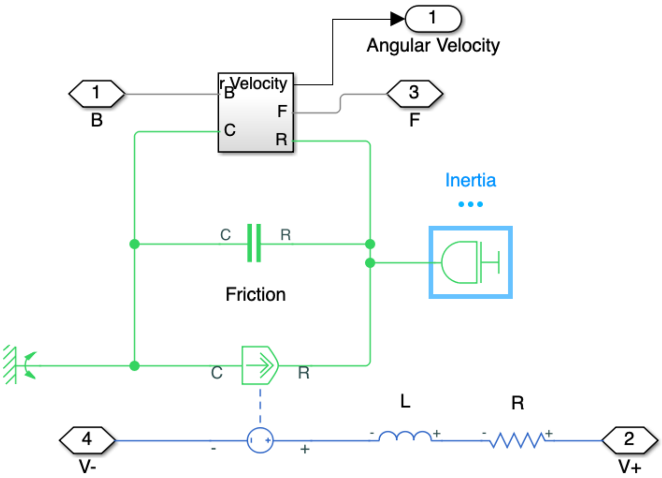


Fig. DC Motor Subsystem in Simscape

The rotational multibody block consists of ideal torque sources, distance constraint, angle constraint, torque sensor and transform sensor and the output is the angular velocity of the motor shaft.

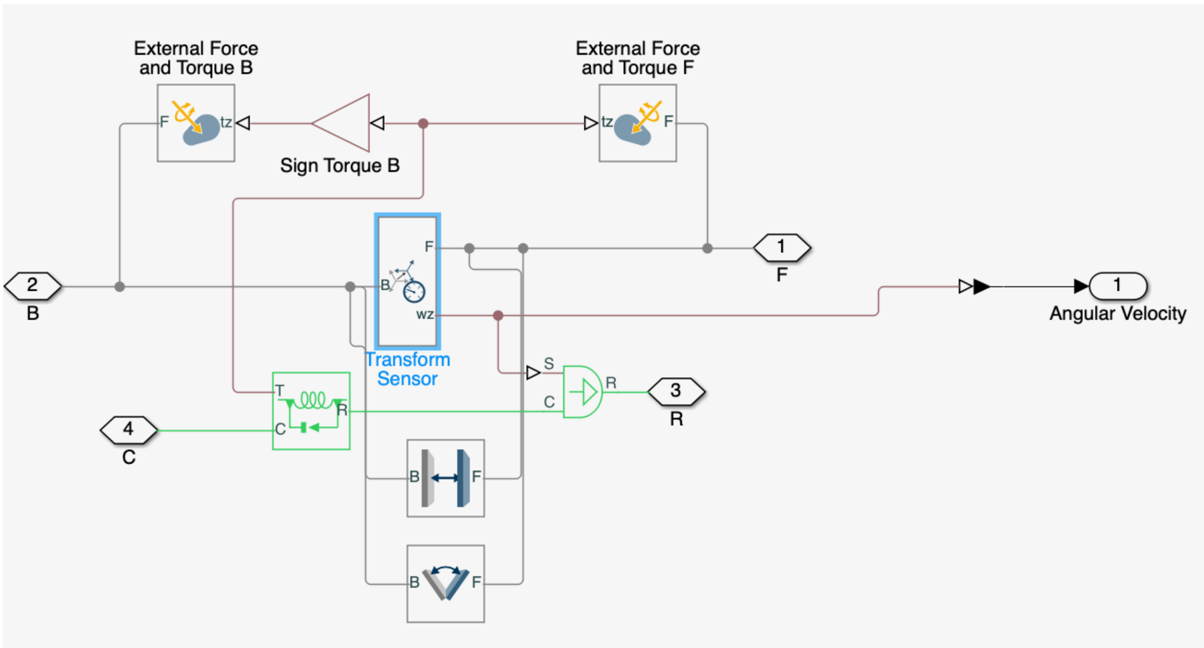


Fig. 7 Rotational Multibody Block in DC motor

Finally, we can calculate the angular momentum from the angular velocity using the formula below:

$$\vec{L} = I\vec{\omega}$$

,

Where $\vec{L}$ – angular momentum of the flywheel.

I – Moment of Inertia tensor of the flywheel.

$\vec{\omega}$ – Angular velocity vector of the flywheel.

IV. Thruster Subsystem

A. Overview

Two centrifugal pumps (blowers) were used to create the suction force for the incoming air, and it provides a velocity to the air using rotational energy of the impeller blades. Then from each centrifugal pump, the airflow got distributed into 8 parts which results in a total of 16 thrusters. Each thruster is either in the ON or OFF position depending on the voltage input and based on a logic(matrix), the nozzles that need to be opened for a specific value of force and moment is determined. Four thrusters were placed on each vertical face of the spacecraft simulator resulting in 16 thrusters to control the translational and rotational motion of the spacecraft simulator in the 2D plane, resulting in 3 degrees of freedom (F_X, F_Y, and M_Z) for the model spacecraft.

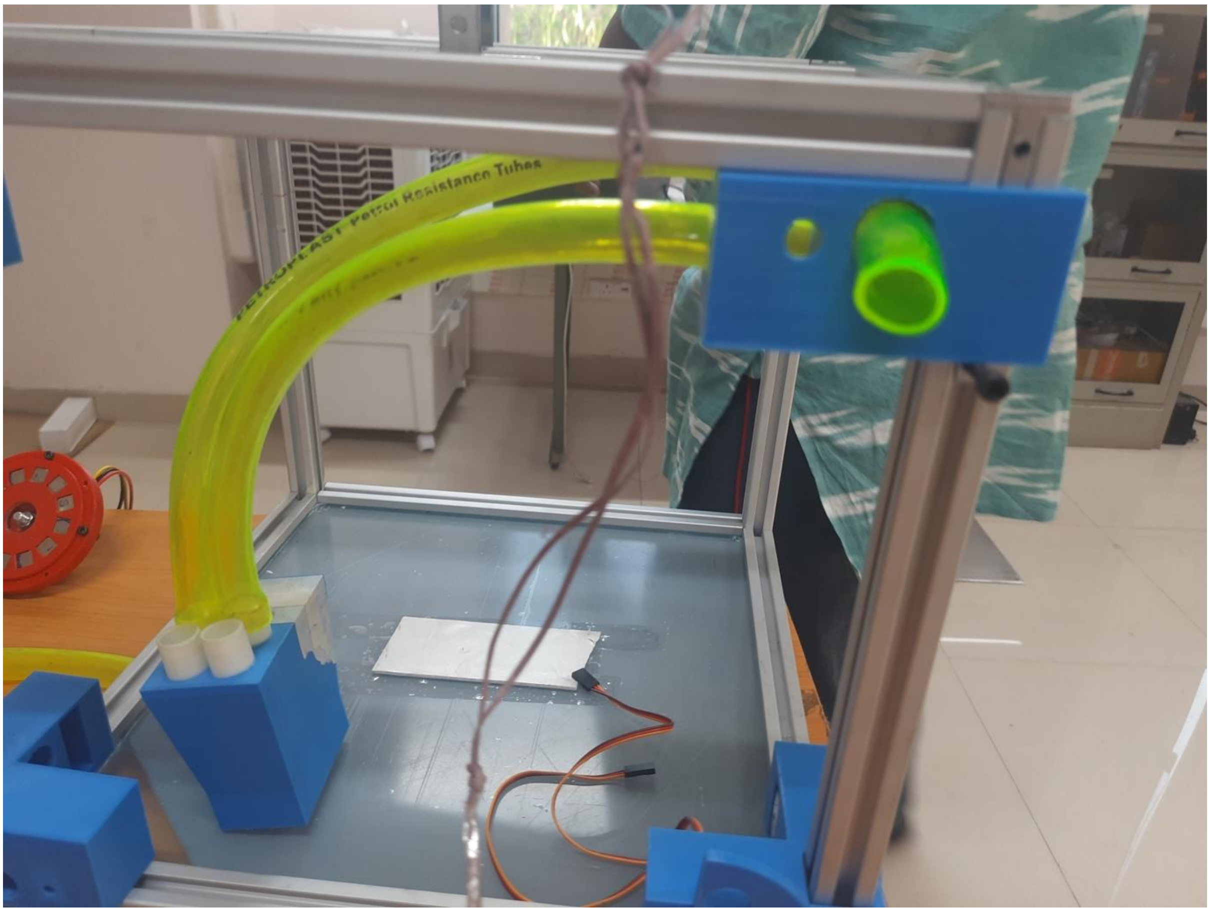


Fig. Relative Position of Thruster pipe and nozzle position in the 3 DoF spacecraft Simulator

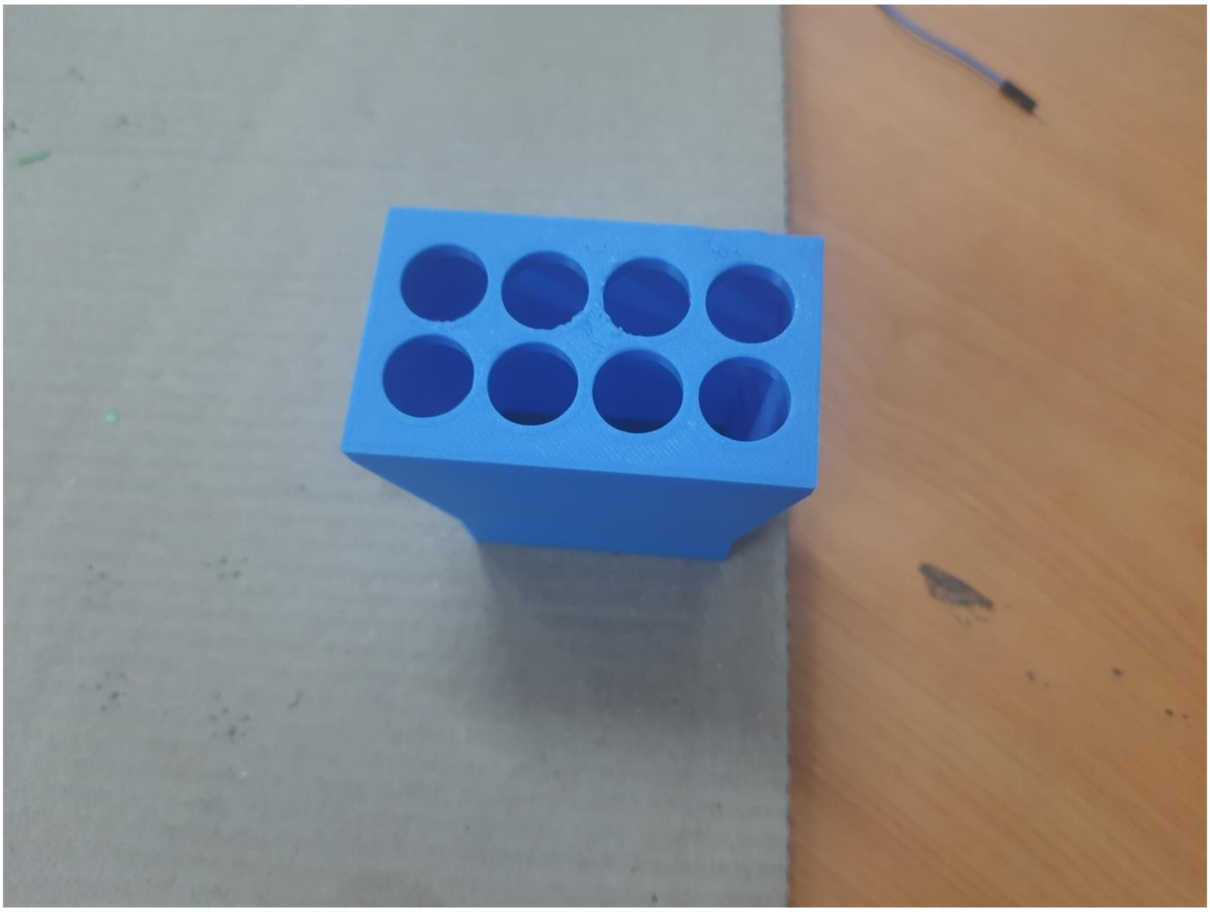


Fig. Blower connector used to distribute the airflow from each centrifugal pump to 8 thrusters

B. Calculation of thrust

For calculating the thrust, we have to calculate the velocity of the air coming out from each of the thruster first, which is the same as the velocity of the air coming out of the centrifugal pump, assuming no losses due to leakage of air and other factors. The centrifugal pump runs on 12V DC supply. It was found out that the velocity from the pump was directly proportional to the input voltage. The input voltage was varied through the PWM (Pulse Width Modulation) signal. The experimental setup used for calculating the thrust and the detailed explanation for thrust calculation is given below:

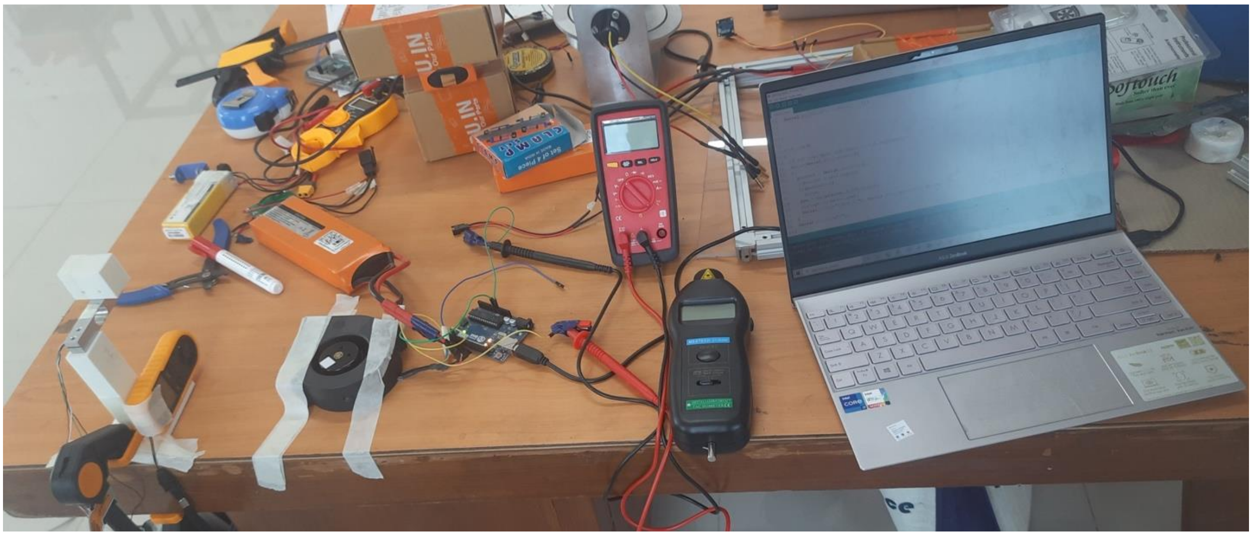


Fig . Experimental setup for the calculation of thrust

The experimental setup consists of an anemometer, which is used to measure wind speed, which is firmly attached to the table using clamps. The anemometer is situated at a distance of 10 cm from the centrifugal blower. The centrifugal pump is connected to the 12V DC power supply, and it is also connected to the Arduino UNO board. The multimeter was used to ensure that the circuit is properly connected, and the power is reaching the centrifugal pump. It is also used to measure the voltage of the power supply. A laser Tachometer was used to find out the rpm of the motor at different voltages. For measuring the rpm, a piece of reflective tape was attached to the motor of the centrifugal pump, and it reflects the laser beam of the tachometer. Finally, the Arduino UNO board was attached to the laptop which had Arduino software installed. The code was written in Arduino programming language to run the motor at different voltages by varying the PWM signals. This is because as current drawn increases, the voltage drop due to battery's internal resistance increases and so less voltage is available to the load(blower motor). Two sets of velocity readings were taken and the average of the two readings was used to determine the relationship between the voltage and the velocity. The equations used in determining the relationship between the velocity and the voltage are given below:

$$Percentage = PWM * 100/256$$

Where PWM is an integer ranging from 0 to 255 and percentage varies from 0 to 100

$$Average\ Voltage = (Percentage * voltage\ measured)/100$$

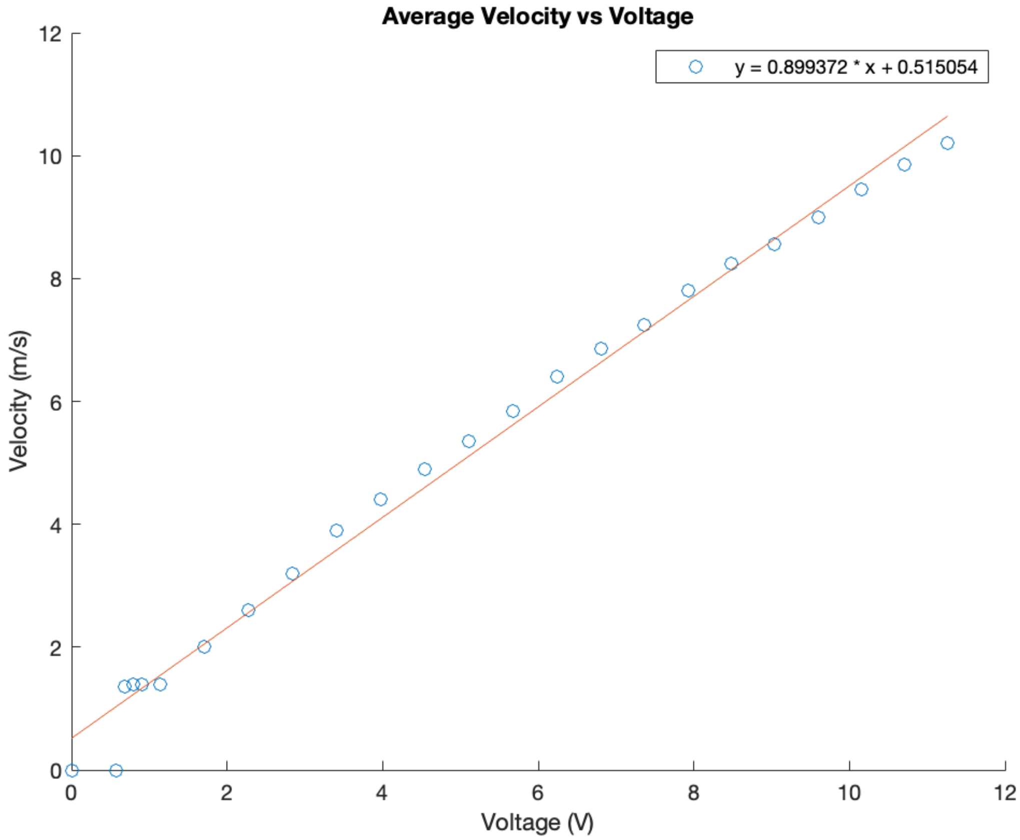
Where Average Voltage is the voltage reading of the multimeter and the percentage is the value calculated from the earlier formula.

$$Average\ velocity = \frac{Velocity\ reading\ 1\ +\ Velocity\ reading\ 2}{2}$$

The velocity lookup table thus created using the above equations is given below:

PWM	Percentage	RPM	Voltage Measured	Average Voltage	Velocity reading 1	Velocity reading 2	Average velocity
0	0	0	11.36	0	0	0	0
12	5	0	11.36	0.568	0	0	0
15	6	920	11.36	0.6816	1.4	1.3	1.35
17	7	921	11.36	0.7952	1.4	1.4	1.4
20	8	920	11.36	0.9088	1.4	1.4	1.4
25	10	922	11.36	1.136	1.4	1.4	1.4
38	15	1365	11.36	1.704	2	2	2
51	20	1800	11.36	2.272	2.6	2.6	2.6
63	25	2200	11.36	2.84	3.2	3.2	3.2
76	30	2690	11.36	3.408	3.9	3.9	3.9
89	35	3090	11.36	3.976	4.4	4.4	4.4
102	40	3460	11.36	4.544	4.9	4.9	4.9
114	45	3790	11.35	5.1075	5.3	5.4	5.35
127	50	4140	11.35	5.675	5.8	5.9	5.85
140	55	4515	11.34	6.237	6.4	6.4	6.4
153	60	4840	11.34	6.804	6.8	6.9	6.85
165	65	5150	11.33	7.3645	7.2	7.3	7.25
178	70	5495	11.32	7.924	7.8	7.8	7.8
191	75	5840	11.31	8.4825	8.3	8.2	8.25
204	80	6085	11.3	9.04	8.6	8.5	8.55
216	85	6350	11.29	9.5965	9	9	9
229	90	6655	11.28	10.152	9.5	9.4	9.45
242	95	6965	11.27	10.7065	9.9	9.8	9.85
255	100	7205	11.26	11.26	10.2	10.2	10.2

The variation of velocity with voltage is plotted in MATLAB and the plot is given below:



Using linear regression and best fit line, the relation between the voltage and velocity was determined as follows:

$$Velocity = 0.899372 * Voltage + 0.515054$$

C. Simulink Model of Thruster

The thruster subsystem is constructed in Simulink with voltage as the input and the force from one thruster as the output. The relation between voltage and velocity is used in the subsystem in the form of a lookup table. The total mass flow rate is then obtained by multiplying the velocity with the density and the area, i.e.

$$\dot{m} = dm/dt = \rho A v$$

where $\dot{m}$ - mass flow rate
A - Cross- sectional area of the nozzle

v – velocity of air coming out of the nozzle

The total force is then obtained by multiplying the mass flow rate with the velocity of air, i.e.

$$F = \dot{m} * v = \rho A v^2$$

Finally, the force is divided by 8 to get the individual force for each nozzle. This is because one centrifugal pump supplies the airflow for eight thrusters. The Simulink model of the thruster subsystem is shown below

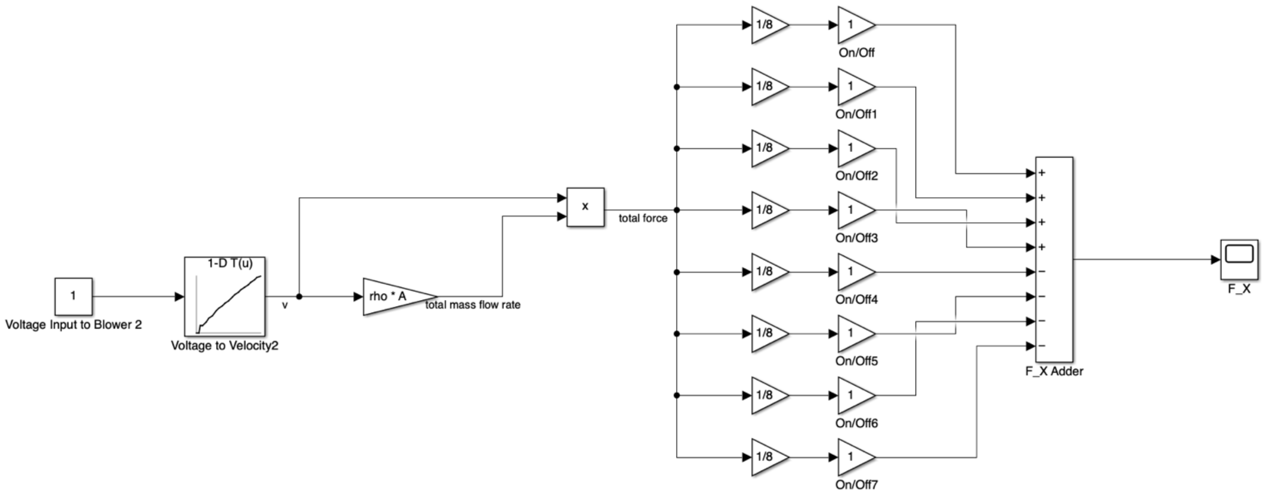


Fig. Thruster subsystem model in Simulink

Finally the forces can be summed to provide the resultant force vector in the X and Y directions and moment about the Z direction can also be found.

References

1. https://robokits.co.in/motors/rhino-ig32-12v-20w-dc-motors/dc-servo-encoder-12v-motor/rhino-500rpm-6kgcm-12v-dc-planetary-geared-quad-encoder-servo-motor