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Designing, constructing and testing a passive, two-sided, and efficient de-orbiting mechanism for CubeSats

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In this article, we analyze the existing de-orbiting mechanisms in the world and their different types for Nano satellites, also known as CubeSats. Moreover, a new passive and efficient design of the de-orbiting mechanism for the CubeSats has been proposed. Utilizing de-orbiting mechanisms is important in Nano satellites or CubeSats to prevent the production of space debris in LEO (low-earth orbit), and in NASIR-1 CubeSat. Sail Drag method was used for such purpose. In this method, the satellite is deorbited using passive two-sided de-orbiting approach in 1.7 years on average, or less than a maximum of 2 years. Software analysis is used to calculate the membrane size and the required boom mechanisms in LEO, 600 km from thrte earth's surface. Drag sail is designed using the software and the prototype as well as the final version for engineering model are made and tested. The passive two-sided sail drag design of NASIR-1 is a more efficient mechanism compared to active, four-sided models in terms of volume, weight, and the required electrical power and it offers a larger available external surface on CubeSat's surfaces.

Keywords: *Drag Sail mechanism, De-orbiting, CubeSat, Nanosatellite, Two-sided, Passive, Low-Earth Orbit (LEO)*

Introduction

In recent decades, the increase in space debris in LEO has become a threat to the safety of astronauts during spacewalks, as well as the International Space Station (ISS), and various operational satellites in different orbits. It is prognosticated that space debris will keep increasing as more spacecraft are launched; pieces 1 to 10 cm in diameter will increase to 750000 pieces and over 29000 pieces more than 10 cm in diameter will exist in LEO and geo stationary earth orbit (GEO). In general, it can be said that over 94% of space launches turn into space debris, and the overall weight of 64% of the debris can be up to 7500 tons [1]. That is why developing mechanisms to prevent the devices used in space from becoming space debris is of great importance so that we can use these high value orbits safely in the future.

De-orbiting mechanisms are varied according to the required budget, type of missions, and their orbits. There are various mechanisms, which have been illustrated in table 1, defined based on different needs and circumstances for CubeSat for de-orbiting based on conducted survey, some of which are: Sail Drag, Solar Sail, Inflatable drag devises (balloon), Solar Balloon, and Inflatable drag devises.

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Table 1 shows de-orbiting mechanisms for various CubeSats

Name of CubeSat's or de-orbiting mechanism	Type of de-orbiting mechanism	Name of university or company or organization	References
A Scalable Drag Sail	Sail drag	Georgia Institute of Technology	[2]
CanX-7	Sail drag	Toronto University of Technology	[3,4,16]
AEOLDOS	Sail drag	Glasgow UK, Technical University of Munich	[5]
NANOSAIL-D2	Solar sail	NASA	[6]
DRAG-NET	Sail drag	NASA	[7]
EXO-BRAKE (TechEdSat - 3,4,5,6)	Inflatable drag devises (balloon)	NASA	[8]
RODEO	Inflatable drag devises	University of Colorado	[9]
SPACE FAN	Inflatable drag devises	Istanbul Technical University	[10]
Cranfield De-Orbit Mechanism (DOM)	Sail Drag	Cranfield University	[11]
Inflatable (DRS)	Inflatable drag devises	University of Arizona	[12]
3 Unit Satellite De-orbiting Mechanism	Inflatable drag devises	Istanbul Technical University	[13]
Balloon	Solar Balloon	University of Strathclyde	[14]
Freedom	Inflatable drag devises	Tohoku University	[15]
Terminator Tape	Inflatable drag devises	Pennsylvania State University, NASA	[23]
Terminator Tether	Inflatable drag devises	Gainesville	[24]
Development of a generic inflatable	Inflatable drag devises	TU Delft	[25]
Inflatable Rigidisable MAST	Inflatable drag devises	University of Surrey	[26]

As it is clear in table 1, different CubeSats use various mechanisms to de-orbit. In fact, the CubeSat mission and its defined requirements for the de-orbiting sub-system have a direct role in deciding the type of mechanism used. Sun sail is suitable for moon or Mars missions since the solar light particles reach the sail with a fixed angle because in earth orbit, this angle is constantly changing which makes changing the direction of the sail a necessity to produce an effective force for de-orbiting. This requires precise attitude control (ADCS) and consumes a lot of electrical power. Most inflatable drag devices and mechanisms do not provide a sufficient and suitable surface for aerodynamic drag, which increases the time needed to reduce altitude, often exceeding the time required for sail drag. Different sail drag designs have been presented, each with its own pros and cons. Some of these designs, such as the one offered by Georgia Institute of Technology [2], have many capabilities and can be improved to suit CubeSats and microsatellites with various sizes, but they require electrical motors and energy to open the booms, which is why they are categorized as active mechanisms. The power consumption of the aforementioned motors should be considered too. The overall specifications of this design are shown in table 2. With a weight of 750 grams and dimensions equal to 0.5U, making its weight rather high despite its suitable dimensions.

Table 2 shows sail drag mechanism specification of Georgia Institute of Technology [2]

Active sail drag specification	**Value**
System mass	0.75 kg
System dimension	51.25*100*100 mm^3
System drag area	1.13°
Deployment method	Motor driven
Boom type	SHEARLESS
Boom length	1 m
Anti-Blossoming mechanism	One contact point per spring
Sail material	CP1/Corin
Sail thickness	5 µm
Sail folding	Frog legs

In contrast, the drag sail used in CubeSat CanX-7 [4] uses a passive mechanism, in which by using the energy stored from booms after the door container opens, the booms open automatically from the four sides of CubeSat. Unfortunately, the mass, volume, and electrical power specifications of this mechanism are not offered, making it impossible to be compared with other designs. The design used in AEOLDOS CubeSat [5] is another example of passive sail drag. Its volume is around 0.4U and weighs around 372 grams. In this design, the membrane holder booms protrude from the floor of the mechanism and CubeSat's bottom surface rather than its sides, which means this mechanism must be installed at either end of the CubeSat. This also means that antennas or solar cells cannot be installed on the surface below, which is one of the important surfaces on the CubeSat. In general, we can say that the process of selecting or designing a suitable mechanism to de-orbit a CubeSat greatly depends on not only the functionality and capabilities of the mechanism itself, but also the system requirements for that mechanism. In this article, we attempt to select the best de-orbiting mechanism in accordance to the system requirements of NASIR-1, 3U CubeSat, and then, we design and build it based on such requirements, and finally, test it.

Nasir-1 CubeSat

NASIR-1 is the first CubeSat designed and built by K. N. Toosi University of Technology. Based on CubeSat standards, 1U CubeSats should be 10*10*10 in dimensions and weigh 1.33 kilograms. NASIR-1 CubeSat follows 3U CubeSat standards: it weights 4kg and is 34*10*10 cubic centimeters. This CubeSat has three primary missions, which include air traffic control (ADS-B), inter-satellite link (ISL), and de-orbiting mechanism (passive, two-sided Sail Drag). NASIR-1 CubeSat's orbit is SSO and its orbital altitude is defined 600 km. Currently, this CubeSat is in assembly, integration, and engineering model testing (AIT) phase. Figure 1 shows this satellite's schematic with communication antennas open, which is designed in software. The Nasir-1 CubeSat's overall system and subsystem specification are shown in table 3.

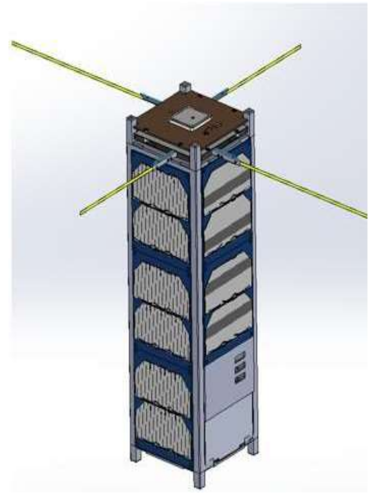

Figure 1 shows Nasir-1, 3U CubeSat

Table 3 shows the overall system and subsystem specifications of NASIR-1 CubeSat.

Nasir-1,3U CubeSat Specification	Value
Dimension	10*10*34 cm³
Mass	4 Kg
Power Generation	2-8 W
Regulated Bus Voltage	3.3, 5 V
Unregulated Bus Voltage	8.2~ V
Battery Capacity	6.4 Ah
3 Axis Attitude Control	±10°
Command Uplink	145 M Hz
Telemetry Downlink	436 M Hz
TT&C modulation	FSK
Thermal control	Passive
Data storage	1.5 GB

De-orbiting subsystem requirements

Based on the requirements set in CubeSat standards [17], disposal process should be completed in less than 25 years. In other words, the designed CubeSat should include mechanisms to expedite de-orbiting process and to reduce it to less than 25 years. An important point in NASIR-1 CubeSat's missions is in-orbit testing of the de-orbiting mechanism (passive, two-sided Sail Drag). As a result, altitude reduction process of this CubeSat should be confirmed using GPS data transferred through communication links; therefore, the CubeSat's life span for attitude determination and data transfer is important in addition to the 25-year timeframe. Considering the life expectancy of two years for NASIR-1 CubeSat parts and devices, the de-orbiting mechanism is required to de-orbit the satellite in less than two years.

We can name the following as other requirements determined for the de-orbiting subsystem:

Passive system without the need to constant consumption of energy

Volume budget less than 1U

Power budget less than 8 watts, only once

Mass budget less than 700 grams

Using the maximum of two sides from a standard unit of 1U

The fifth requirement is determined due to the structural requirements to place the CubeSat's magnetometer on one side of the mechanism's structure, and pass PIFA antenna's connection cable through the bottom surface of NASIR-1 Nano satellite.

Selecting the de-orbiting mechanism in NASIR-1 CubeSat

There are different approaches to de-orbiting satellites, sending them to useless orbits, or reducing the orbital altitude, and burning them in the atmosphere. The approaches used to de-orbit satellites that result in reducing speed or altitude are as follows: using thrusters through consecutive pulses, sun sails (as charged particles of the sun hit the sail), tethers, balloon drag, and sail drag mechanisms (as atmosphere molecules hit the sail membrane and produce the required aerodynamic drag to reduce the speed and orbital altitude.) The advantages and disadvantages of each mechanism are given in table 4.

Table 4 shows varied de-orbit mechanisms for satellites and CubeSat [3]

De-orbit approach	Active/ Passive	Killer Trades
1-Propulsion	Active	Requires high total impulse Requires active pointing Requires long term fuel storage
2-Solar sail	Active	Requires active pointing Susceptible to jamming Susceptible to MMOD degradation
3-Drag tether	Passive	Large characteristic dimension Deployment complexity Susceptible to jamming Inclination limited
4-Inflatable drag device	Passive	Requires long term, leak free storage of compressed air Altitude limitation Susceptible to jamming Susceptible to MMOD degradation
5-Mechanically deployed device (Drag sail)	Passive	Requires mechanical storage energy Altitude limitation Susceptible to jamming Susceptible to MMOD degradation

Table 4, methods 2, 3, and 4 cannot be used in CubeSats because they go beyond the weight, power, and volume budgets determined in the requirements of the de-orbiting mechanism based on our system NASIR-1 CubeSat. Also, the ACS subsystem should always be active. Methods 1 and 5 in the table are more suited to CubeSat standards and our system requirements, thus they require further analysis. In addition, reviewing the de-orbiting mechanisms in similar CubeSats shows that the best de-orbiting method for such satellites is sail drag. To affirm this claim, software analyses have been conducted for both sail drag and thruster de-orbiting mechanisms. Between cold gas and ion thrusters, the latter is deemed more suitable for CubeSats since it has higher reliability and ISP, and can de-orbit the satellite after a longer period of time. Cold gas thrusters used in Nano satellites are often for ADCS subsystem. If used for de-orbiting, these thrusters require more fuel and operational time compared to ADCS function, which necessitates greatly increasing the tank's size, while ion thrusters can easily fulfill the requirements. As a consequence, the analysis presented here will be limited to ion thrusters. The results of this analysis for de-orbiting NASIR-1 CubeSat from 600km orbit and directing it to earth's atmosphere, or 120 km orbit, are shown in table 5.

Table 5 shows the ion propulsion analysis results for de-orbiting a 3U CubeSat

Fuel consumption: 0.63 Kg	Thrust: 0.165 N
ΔV: 0.04697 Km/s	ISP: 3800 S

According to the results, the fuel needed for ion thruster is still significant, and cannot fulfill the weight requirement for the de-orbiting mechanism. As a result, the only practical mechanism in this stage is sail drag, based on the choices and conclusions mentioned here. The main parts of sail drag are sail membrane, booms, meter booms mechanisms, hatch opening board, and the storage case of the sail membrane. In what follows, we explain the process of designing and building this mechanism.

Designing sail drag mechanism for NASIR-1 Nano satellite

The algorithm of all stages of designing, building, and testing the sail drag are simplified and given in figure 2. Based on this algorithm, the membrane surface of the sail drag is first calculated using software to determine its dimensions. Next, the material used in the membrane and how it folds are determined. In the next stage, the mechanism's structure is designed based on system and structural requirements, and opening mechanisms of booms and holding door are planned. In the following lines, we will explain how each of these stages is done.

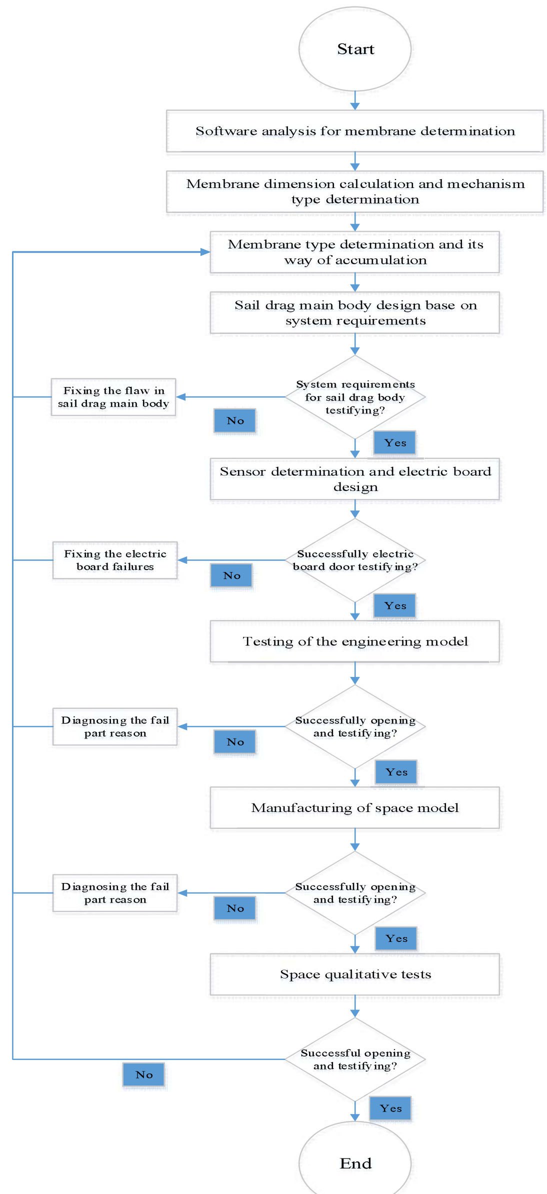

Figure 2 shows the algorithm for sail drag designating, constructing, and testing

Calculating the membrane surface of sail drag mechanism

Software calculations were utilized to calculate the required membrane surface of the sail drag. To do so, the time it takes to exit 600km orbit and to reach an altitude of 120km, which is the altitude the CubeSat enters the earth's atmosphere, is calculated while taking the material of the membrane into account. These calculations are done for membranes with surfaces of 0.25, 0.5, 1, 1.5, 2, 3, and 4 square meters, and the results are depicted in figure 3.

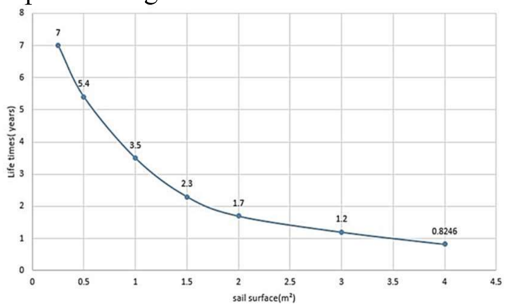

Figure 3 shows years needed for various sail drag membranes in order to de-orbit

In order to analyze the exiting orbit in different levels with two-line-element (TLE) profile, the calculations are done while considering information such as drag coefficient of 2.2, Jacchia 1970 Lifetime atmosphere density model, and the SolFlx0909 Schatten.dat solar model.

As figure 3 shows, the minimum membrane surface should be 2 square meters to achieve a time less than 2 years. Surfaces with 3 and 4 square meters can fulfill the orbit exit requirement in spans less than 2 years. Various factors will be considered to choose the best option among the choices of having a membrane with a surface of 2, 3, or 4 square meters. According to the completed calculations and analyses, the weight of the booms is 15 grams per meter, the opening mechanism volume of the booms is half a centimeter of its drawer's diameter per meter, and the number of folds for a membrane with 2cm thickness is 50 per meter. To calculate the mass of the booms, each meter of boom is multiplied by the weight of the boom for 1 meter. Considering the dimensions of the membrane, the number of folds depends on the volume of these dimensions, and for 2 meters of membrane, 100 folds are needed in the shape of a trapezoid. The space required to hold this number of folds will increase parallel to the increase in the membrane dimensions. In table 6, container dimensions to hold the number of folds and the booms' weight per meter and the time (years) required to exit the orbit are used to determine the dimensions of the sail membrane.

Table 6 shows detail information for trade of between 0.5, 1, 1.5, 2, 3, 4 m² sail drag membrane and its boom mechanisms

Sail surface volume (m²)	Number of years to de-orbit	Volume of de-orbiting mechanism	Mass of de-orbiting mechanism	Reason of rejection	Accepted or Not
0.5	5.4	Less than 1 U standard CubeSat's volume	Less than 700 gr system's requirement , {25 membrane folds = 30 mm space needed}, {15*4 = 60 gr mass of meters}	Number of years for de-orbiting. Exceeding 2 years of requirement	NOT OK
1	3.5	Less than 1 U standard CubeSat's volume	Less than 700 gr system's requirement, , {50 membrane folds = 60 mm space needed}, {15*4 = 60 gr mass of meters}	Number of years for de-orbiting. Exceeding 2 years of requirement	NOT OK
1.5	2.3	Less than 1 U standard CubeSat's volume	Less than 700 gr system's requirement , {75 membrane folds = 80 mm space needed}, {15*4 = 60 gr mass of meters}	Number of years for de-orbiting. Exceeding 2 years of requirement	NOT OK
2	1.7	0.6 U	630 gr {84 gr for meters}, {100 membrane folds = 90 mm space needed in wide of from 92 mm space }	Accepted Meet all the requirement	OK
3	1.2	Less than 1 U standard CubeSat's volume	More than 800 gr Exceeding system's requirement 3 meter membrane needs 2 meter length boom {15 gr * 8 meter= 120 gr for meters}, {150 membrane folds = more than 10 cm} need for stronger springs and thicker meter holders	Overweight More than 700 system's requirement , need more space for folded membrane	NOT OK
4	0.83	Less than 1 U standard CubeSat's volume	More than 800 gr Exceeding system's requirement 3 meter membrane needs 2.5 meter length boom {15 gr *10 meter= 150 gr for meters} , {200 membrane folds = more than 10 cm} need for stronger springs and thicker meter holders	Overweight More than 700 system's requirement, need more space for folded membrane	NOT OK

In able 6, surfaces with 0.5, 1, and 1.5 square meters will need more time to exit the 600km orbit due to the lack of the sail membrane's surface size. The aforementioned choices are also rejected because they do not fulfill the requirement to exit the orbit in less than 2 years. The weight budget for the mechanisms of these surfaces is acceptable, and they will definitely have a simpler and lighter axis due to the shorter length of their boom and the smaller pressure exerted on their axis. While the surfaces that are 3 and 4 square meters wide offer an ideal orbit exit time, the weight of their booms and mechanisms is increased; judging by the calculations in the table, this will exceed 700 grams that does not meet the system requirements. A surface that is 2 square meters wide fulfills the requirements in terms of both the time to exit the orbit and the amount of its weight and volume. Consequently, it is chosen as the surface area of the membrane. According to the presented information, the membrane's surface is two square meters, and it takes 1.7 years on average to exit the orbit. The software analysis is calculated, which has been illustrated in figure 4, for a 4-kilogram CubeSat in the orbit 600km from the earth's surface, while taking into account the solar flux and the average atmospheric density of different orbital altitudes.

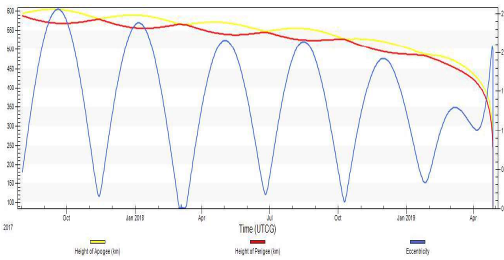

Figure 4 shows the eccentricity, height of perigee and height of apogee changes for 2m sail drag membrane during de-orbit phase

In figure 4, the amount of time required to exit the orbit for a two square meter surface of sail drag is calculated using software analysis. According to figure 4, considering the mentioned assumptions and a membrane with the surface area of two square meters, the period required for NASIR-1 CubeSat to exit the orbit is calculated through software calculations, and it equals 1.7 years.

Choosing between passive and active de-orbiting mechanism in sail drag

Opening the sail drag booms requires a specific mechanism that functions by either stored mechanical power or electrical power generated by a small motor. In active method, there is at least one motor to generate the electrical power needed to open the booms by rotating the axis on which the booms are placed. The mechanism that includes an electric motor will indubitably require more space and electrical power, and it will be heavier. On the other hand, the passive mechanism functions by the stored mechanical energy in the booms during integration. This method has less mass and volume, and requires no electrical power to open the booms. To conclude, based on the power consumption requirements, the passive de-orbiting mechanism of drag sail is chosen for NASIR-1 nanosatellite.

Two-sided or four-sided opening design for sail drag

The four-sided design is too heavy and too large for de-orbiting mechanism of sail drags with 1U and 2U CubeSat standards. It also makes the construction and design quite challenging. The sail will be four-sided while the system is required to have parts installed next to the sail. Finally, more electrical power is required to open the four doors and to activate the sensor on each side, and it will be heavier. Consequently, due to the previously mentioned reasons, the two-sided design for de-orbiting mechanism of sail drag is designed, built, and tested in NASIR-1 CubeSat. In order to fulfill the surface required, we should divide the required amount, which is 2 square meters, by 2 and calculate two trapezoid-shaped surfaces amounting to two square meters. Based on the calculations and the two-meter surface required, the dimensions of each sail membrane for NASIR-1 CubeSat are depicted in figure 6. Being two-sided does not create any problems for the de-orbiting mission, and will have less power consumption, vertical volume, and mass. It is also possible to have access to the surface under the Nano satellite in this way, since this surface is very important for different antennas of telemetry and tele-command (TT&C) subsystems.

Calculating the size and the shape of the sail membrane and its boom-mechanisms

The design process of the sail drag based on the algorithm is shown in figure 2. The surface is determined 2 square meters for 3U CubeSat in 600km orbit. The length and dimensions of its booms are presented in figure 5. The sail membrane booms are calculated to be 1.3 meters. To have the 2-square-meter surface, two trapezoids with the same size are selected, and the trapezoid rules are 2, 1.34, 1.34, 0.1 meter that create a two-square-meter surface.

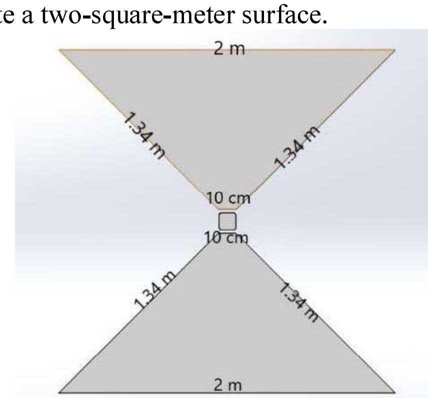

Figure 5 shows the 2m sail drag membrane dimensions for Nasir-1 CubeSat

Determining the type of the boom mechanism of the sail drag and its material

There are two mechanisms for booms or the opening mechanisms of the membrane:

- The typical meters available on the market
- Stem booms [20]

The first choice is the ideal one as it is cheaper, more available, and lighter. The first choice is selected because the second option is not available on the market. In fact, both choices are good for the design, provided that Stem booms are available to build the spatial model. The width of the boom, or the meters used, should not exceed 1.6 cm, and the length of the meter should not be more than 1.4 meters. The length of the booms protruding from the CubeSat should be 1.34 meters. It should be noted that the stored potential energy when the meter is retracted within its ring would be released when it is opened. For the preliminary and engineering model, regular meters mechanism is used to open the sail membrane. Metal rings are used to attach the sail to the booms where the sail is attached to the meter with cords or strings. The rings depicted in figure 6 are used to reinforce the sail membrane when the booms are dragged and the sail membrane is exiting.

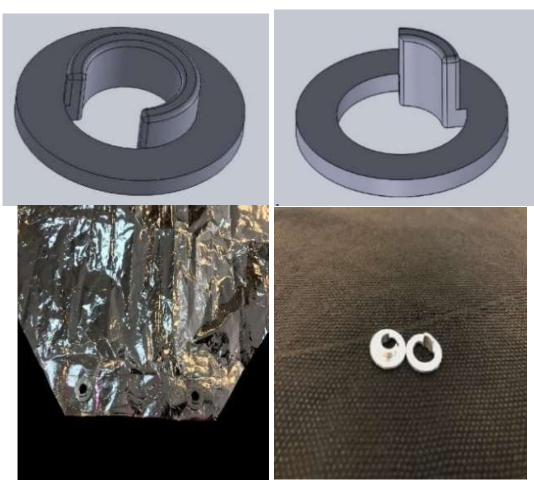

Figure 6 shows new design rings for holding the membrane after exiting with booms

The sail membrane is chosen to be trapezoid because it leads to more surface and aerodynamic drag. The material of the sail membrane stems from statistical design. Two common materials are offered for the sail drag membrane and the best one will be ultimately chosen.

• Aluminized Mylar
• Aluminized Kapton

Aluminized Mylar is cheaper than Aluminized Kapton, but the latter has more resistance to heat, released oxygen atoms, solar radiation, and air drag tolerance. Both options were available, so the Kapton film with aluminum coating was used for the design of the spatial model of the sail membrane, and Mylar was used for the engineering model. The thickness of the selected film is 0.5 micrometer. [21-22]

The method of the folded membrane

Miura-Ori 0 method is used to pull the sail membrane in the mechanism because it opens more easily, and takes less space in the main structure.

Table 7 shows different membrane folding types [3]

Fold type	Folded dimension (cm*cm)	Folded area (m²)	Number of folds	Overall fold thickness (mm)	Number of fold crossovers (circle)	Pattern ratio
Miura-Ori,10	6*6	36	10	2	16	8.2:1
Miura-Ori, 22.5	4*8.7	34.8	9	1.5	17	8.5:1
Miura-Ori, 45	2.5*17.1	42.75	11	1	24	8:1
Miura-Ori,0	4*4.1	16.4	8	2	16	18:1
circular	n/a	n/a	15	n/a	n/a	n/a
Tree leaf (sq)	10.6*3.1	32.86	28	3	25	13.6:1
Tree leaf	10.5*3.1	32.55	20	3	17	10.2:1
Butterfly (sq)	2*21.3	42.6	10	4	49	10.5:1

Miura-Ori zero method is the best option among the items in table 7, and it needs a smaller surface to be placed in the structure of the sail drag. The other choices are rejected since they need more space to be attached to the structure and mechanism, have a more difficult mechanism to open them when the booms open, tend to be more challenging to pull them in retests, and use a more complicated opening mechanism. Figure 7 shows how this membrane is pulled. [1] Figure 8 shows NASIR-1 sail drag mechanism's membrane both folded and opened.

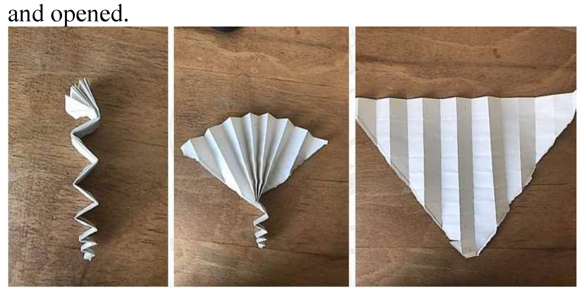

Figure 7 shows Miura Ori 0 folding method by paper

Figure 8 shows Nasir-1 membrane in open and folded shape

Mechanism used to open the door of the sail structure

For the opening mechanism of the doors, the common method of cutting the string by a burn wire is used. In this method, as current is passed through the coiled cord around the string, the heat created will burn and cut the string. Figure 9 shows a sample of this mechanism and its features. In this mechanism, once the string is cut and the door is open, the stored potential energy in the meter mechanism is immediately released which opens the sail membrane. Once the door is open, the attachment of the two rods seen on the board in figure 9, which are attached to the exit mechanism's door, act like a contact sensor for door's opening and confirm that it is open. In contact sensors, thin rods called spring test point are used onboard. The sensor of the de-orbiting mechanism on NASIR-1 CubeSat is a contact sensor; as the door opens, the switch will short circuit and it shows the door of the sail is open.

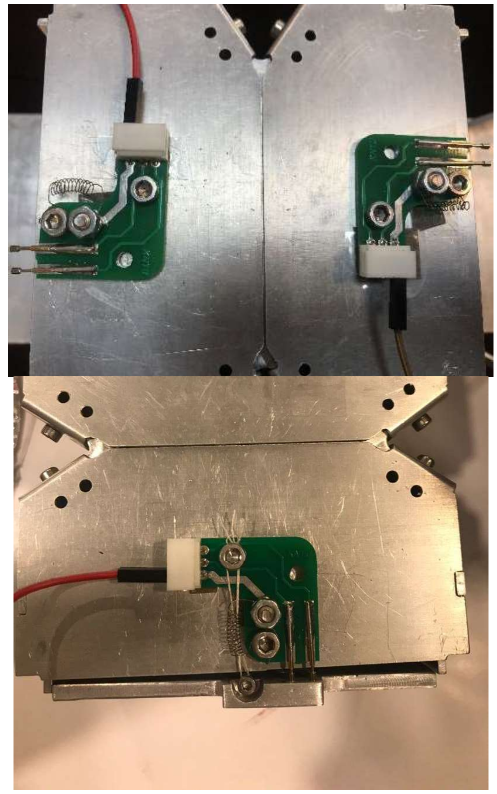

Figure 9 shows sail drag simple electric board for burn wire mechanism and contact sensors with open and close structure door

In figure 9, the short cord that is attached in a coil to the board from two sides can be seen. The holding string in the sail goes through this coil. At the end of the CubeSat's mission, the order to initiate the de-orbiting mission will be issued from the ground station. The electrical current through the coil cuts the string. The sail membrane is opened by the booms and the mission to de-orbit begins.

Design of the main structure and boom mechanisms

The design of the passive, two-sided sail drag for NASIR-1 CubeSat took more than a year for its design, prototype, and redesign to optimize performance. The initial design of the main structure and booms was completed in a simple manner. The test of the initial design was a failure because the mechanism's material was not suitable, there was no rotating axis, the booms did not open well and got out of control, the inner space was not big enough for the booms and sufficient space was not conceived for the sail membrane. To analyze the efficiency of the design, two preliminary designs of the sail structure were made from Plexiglas using 3-D printing, and its opening board was tested successfully. Due to the improper material used in the main structure in this model, the high potential force above the meters damaged the holding pins and some of them broke. To solve this problem, the next model had a structure made of aluminum, and suitable rotating rings, holding and rotating pins and ball bearings were used to rotate the main axis. The sail drag structure material in this model was aluminum 6062. In the sail structure design, ball bearing MR85-2RS made by SMB Company was used; its inner diameter is 5 mm, outer diameter is 8 mm and the width is 2.5mm. The ball bearing is used to rotate the holding rings of the booms in their axis.

After the redesigned model was constructed and tested, the issue of being stuck and the opening persisted in booms and blooming meters. Consequently, the final design was completely fixed and redesigned shown in figure 10. The final design has an opening mechanism consisting of four separate parts, with a spring mechanism to exert force on the meters and a rotating axis on the spring's holding axis to ensure smooth movement of meters and fix the blooming problems. The main structure and the holding case of the sail membrane were rebuilt according to these changes.

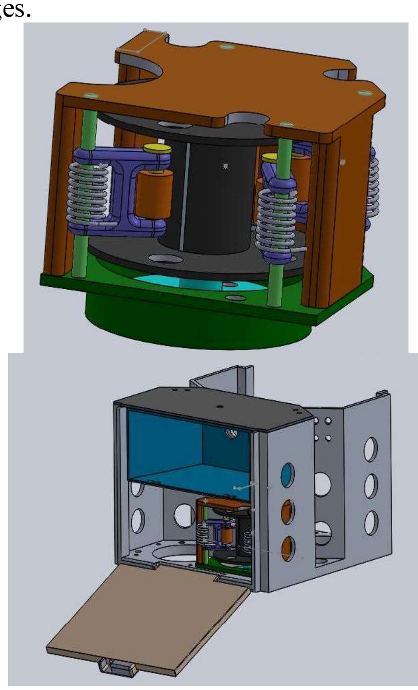

Figure 10 shows the final design for meter boom mechanism

In figure 11, the exploded mode of the boom mechanism has been illustrated with all pieces for one part of the boom mechanism.

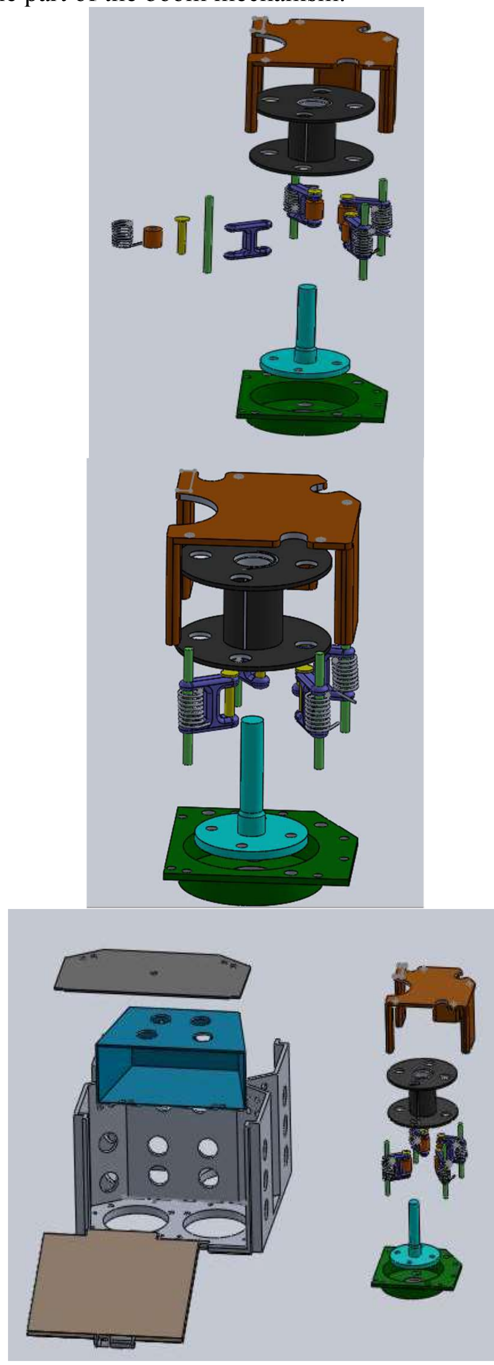

Figure 11 shows the explosion of the boom mechanism

SAIL DRAG AERODYNAMIC AND STRUCTURE LOADS

In reality the booms will deflect and the sail will billow under the effect of aerodynamic loads. Sail billowing and boom deflection is a complex modeling task that depends to a great extent on the material properties and design details. Boom flexure will depend on how the booms are supported at the roots and how the sail is attached to it [27]. In this section a simplified analytical calculation is performed to estimate the reliability and the strength of the boom structure under drag forces.

The most important issue related to boom is buckling and bending due to lateral loads induced by atmospheric drag. Drag force is the external force being harnessed to de-orbit the host spacecraft; therefore, it will be the largest load experienced by the sail. For the purpose of creating the requirements, the loads should be the worst case scenario for nominal activity in order to ensure that the system survives, and for this case there are two factors: altitude and attitude. Drag force increases as the altitude decreases because the density of the atmosphere increases; therefore, the worst case altitude is the lowest operational altitude for the system. Looking at Figure 4, from 400 km altitude due to an increase in drag force, the altitude decreases significantly and the satellite starts to fail. So the altitude of 300 km is generally agreed to be the end of a satellite's orbital lifetime and the beginning of its re-entry phase. The worst case attitude is the attitude where the force in each direction is a maximum. Which sail is perpendicular to the flow [28]. Due to free molecular behavior of atmosphere in altitude above 100 km, the drag force can be estimated by [28]:

$F_{drag} = 0.5 * C_d * \rho * A * V^2$ (1)

Where ρ is the atmospheric density, V is the speed of the satellite in the orbit, A is its cross sectional area perpendicular to the direction of motion, and Cd is the surface drag coefficient. The drag surface area is one of the important parameters, which has a drastic effect on the satellite lifetime. With the increase in the exposed drag surface area of the satellite, the resulting drag force acting on a satellite increases, and thereby reduces the satellite orbital lifetime. As mentioned before the worst case is where the sail is perpendicular to the flow, so cross sectional area for one sail is triangle with an area of 0.892 m^3. Drag coefficient is considered 2.5 [28]. Another term in drag force equation is the atmospheric density which is proportional to altitude of satellite and by decreasing the altitude, the atmospheric density increases. So if the end of satellite orbital life time is considered to be at 300 km, the maximum density at this altitude leads to the maximum drag force. The equation of atmospheric density is derived from reference [29]. Another important parameter in drag force equation is the velocity of satellite. Satellite velocity is proportional to the altitude of satellite as well, which increases by decreasing the altitude. So similar to atmospheric density, the maximum figure for drag force because of velocity happens at altitude of 300 km. Equation of orbital velocity of satellite is:

$$V = \sqrt{\frac{GM}{R+h}} \qquad (2)$$

Where M is the mass of the earth, R is the radius of the planet and h is the distance of the satellite from surface of the planet. Which in this study is from 300 km to 600 km. Considering the above parameters, the drag force is variable with altitude and the maximum of this number is at 300 km altitude. In figure 12, the curve of drag force versus altitude is presented. The maximum drag force obtained is about 0.0097 N at 300 km altitude.

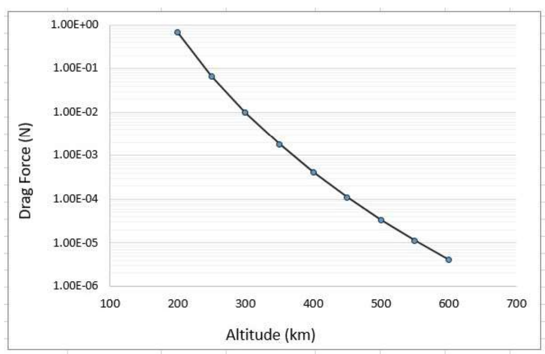

Figure 12 Drag force applied on boom vs. altitude

Timoshenko beam theory can be used to determine the first order analytic expressions for boom deflection profiles under lateral loads. Euler-Bernoulli beam theory is valid for small deflections (compared to the length of the beam) and for lateral loads (Figure 13A) [27].

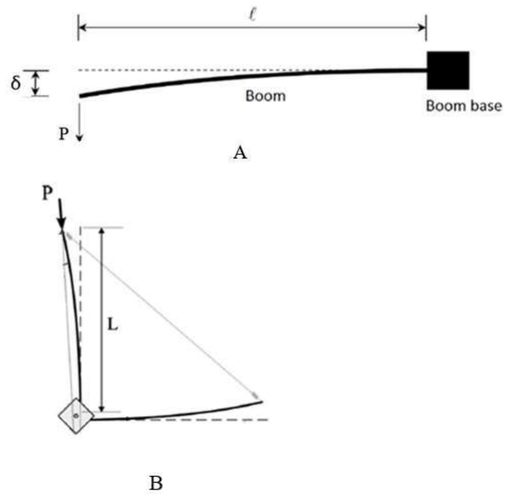

Figure 13 Main applied loads on boom A. Bending B. Buckling [27]

To solve the beam profile equations, the boundary conditions have to be specified, as well as the loading profile along the beam. The booms that support the sail designs studied in this study can be regarded as cantilever beams that are fixed in both position and orientation at one end and free at the other end. The equation that describes the bending profile for a cantilever beam with a load only at the free end is given by [30].

$$\delta(x) = \frac{Fx^2(3L-x)}{6EI} \qquad (3)$$

Where *δ(x)* is the deflection as a function of distance from the root, *L* is the length of the boom, *F* is the drag force acting on the boom tip, which in this study is calculated form equation (1) and depends on altitude. *I* is the second moment of the area taken through a cross section of the boom and *E* is the elastic modulus of the boom material. The material of boom is steel; therefore, the value for *E* is considered as 200 Gpa. As mentioned before, the loads should be the worst case scenario. In real, while drag force is distributed between two booms, the whole load is considered to be applied on one boom which is assumed to act as a concentrated force on the tip of the boom. In this case x will be equal to L. Moreover, the section of boom in the real model has curvature which increases the second moment of area, but in this estimation the simple rectangle section is considered. The value of *I*, is 1.6e-11 m^4. The curve of boom tip deflection versus altitude is presented in figure 14.

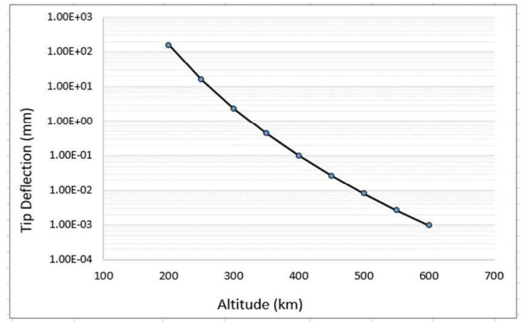

Figure 14 Boom tip deflection vs altitude

Looking at Figure 14, the tip deflection of boom at 600 km is about 0.001 mm and at altitude of 300 km is 2.3 mm which are small. It can be seen from the results that it is at altitudes below 300 km that the deflection becomes significant. Most studies on the subject of sail billow and boom deflection are also concerned with quite bigger sails compared to the designed boom, where billowing is expected to have more influence. On smaller sails such as the dimensions considered for this study, with the anticipated aerodynamic loads, the amount of boom deflection is actually expected to be rather small. By way of illustration, in reference [27] the deflection of a 3.5m long CFRP boom (to support a 25 m^2 sail) is modeled as cantilevered Euler beam under aerodynamic loads. The boom deflection at altitude more than 600 km is evaluated less than 0.005 mm. At altitudes below 350 km that the deflection becomes a significant number of 1 mm which this figure in this study is 0.4 mm. Considering the fact that the length of boom, the geometry, and the material in the latter study is different from this study, so a difference between the results is expected.

Another loading case is the buckling. The axial compressive load can cause the compressive stress or bend the beam sideways. For long slender beams like the booms in this study, buckling causes failure much sooner than the compressive stress. The critical load where a boom will start to buckle is shown in Equation (4), where k is the non-dimensional buckling parameter that is determined by the end conditions of the beam. In this case, the boom was assumed to have one end clamped and one end free so k = 1/4 (Figure 13B) [28].

$$P_{cr} = k\pi^2 \frac{EI}{L^2} \qquad (4)$$

The critical load needed to make the boom buckle is 4.5 N, which in comparison to the maximum force applied on the boom (0.0097 N) is significant.

With calculations performed considering the worst case scenario, it could be said that, deflection of the boom tip is negligible and the magnitude of the forces applying on the boom is lower than the critical buckling load by far. So, the structure is reliable with high safety factor.

Testing the de-orbiting mechanism of the sail drag

Figure 12 shows the parts of the main structure, its door, exiting mechanisms of the booms, the ceiling of the structure, and NASIR-1 CubeSat itself.

Figure 12 shows the final body structure and four-boom mechanism model

After the final design was built, the opening mechanisms of the meters and the opening board of the sail's door were both successfully tested. The electrical power required for opening the door and the time required were also calculated. The power needed to open the doors by the burn wire is calculated to be 3-4 watts and with the battery's unregulated voltage of 8.2 and 400-500 mA, we can burn the string holding the door, where it is attached to the nickel-chrome element wire, in less than 5 seconds; the string's diameter is 20 micrometers. In addition, the meters are completely tested in the mechanisms, and in less than two seconds after the meter doors open, the sail drag membrane opens, which is illustrated in Figure 13.

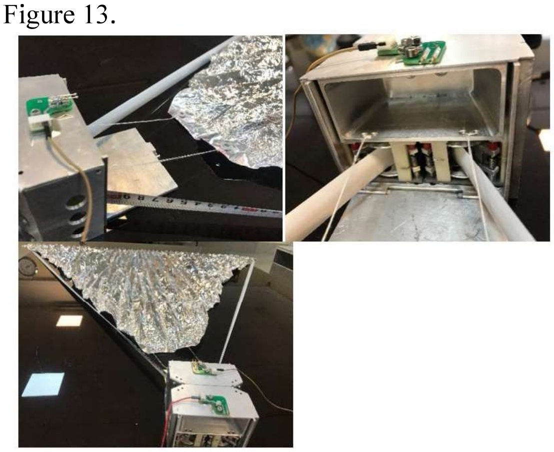

Figure 13 shows the sail drag booms and membrane opened in one side

The overall mass of the sail drag with all its components is 635 grams. The highest weight belongs to the main structure piece that equals 245.4 grams; its weight has increased due to the use of aluminum. In the spatial model, this piece will be made of a lighter material. Using carbon alloys in the main structure, doors, ceilings, and some boom mechanism parts will drastically reduce the mass budget of the sail drag. Figure 14 shows the mass of various parts, consisting of 4 opening mechanisms, two ceilings, 2 holding cases for the membrane, 4 meters, 2 Mylar Aluminum membranes, 1 sail structure, and 2 electrical boards. In the spatial model, the structure and opening mechanisms will indeed be modified to reduce the mass given here.

Figure 14 shows the different components weights for Nasir-1 CubeSat sail drag

Given the sail drag's advantages of being two-sided and passive in terms of mass and power consumption, the weight and electrical power of the 4-sided design of the sail are calculated for further analysis. The weight of the 4-way sail with 8 meters, 1 main structure, 8 mechanisms or 4 cases for each mechanism, will be increased by roughly 1kg. The electrical power consumed to open the doors of the two-sided design is 3 to 4 watts for each door, which culminates to 6-8 watts in less than 7 seconds. However, for the 4-sided design, this number will be increased to 12 to 16 watts to open the doors. As a result, the two-sided passive design is more efficient for the drag sail mechanism of NASIR-1, mainly because the mass budget and the power consumption of the two-sided design are lower. The NASIR-1 Sail Drag mechanism specifications have been illustrated in Table 8.

Table 8 shows specifications of the two-sided, passive sail drag in NASIR-1

Nasir-1 2-Side passive Sail Drag specifications	**Values**
Type	Two-side passive
Dimension	60*100* 92 mm³
Mass of engineering model	635 gr
Power consumption for 2-sides	6-8 w less than 5 seconds
Boom type	Typical meters
Boom length	1.34 m
Sail type	Aluminum Mylar
Fold type	Miura-Ori 0
Sail thickness	5 μm
Drag area	2 m²

Conclusion

In this article, we analyzed the de-orbiting mechanisms in CubeSats as well as the building and testing of the selected design. The best possible choice to de-orbit CubeSats in lower orbits (LEO) has been chosen to be two-sided, passive drag sail. The payload and system team of NASIR-1 designed the sail drag in accordance to the requirements of NASIR-1 CubeSat. The designed sail drag can de-orbit CubeSats from orbits up to 800km above ground in less than 25 years, fulfilling the de-orbiting time requirement. NASIR-1's sail drag, which is currently in the engineering model phase, is quite efficient in terms of mass, power consumption, and usage, and can be suitable for CubeSats from 1U to 12U. This sail is designed, built, and tested in the two-sided and passive format, and it needs less overall mass, electrical power budget and volume in comparison to the 4-sided and the active models, to fulfill the de-orbiting missions of CubeSat.

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