30th Satellite Design Contest Mission Overview

Application category

Idea Section

1. Work information/Applicants information

Work title (less than 20 words) ***Space Lifeboat***		
	Name	Affiliation including faculty, department (Lab) and year of study
Group representative	Koki Hirano	Bachelor Course (3rd Year), Department of Aeronautics and Astronautics, Faculty of Engineering, The University of Tokyo
Group representative (Sub)	Nanami Yasui	Bachelor Course (3rd Year), Department of Mechanical Engineering, Faculty of Engineering, The University of Tokyo Bachelor Course, Aerospace Engineering, The University of Sheffield
Member 1	Jazmin Lindsay-Favelle	Bachelor Course (1st Year), School of Engineering, University of Newcastle
Member 2	Jemimah Woulf	Bachelor Course (2nd Year), Faculty of Engineering, School of Mechanical and Manufacturing Engineering, University of New South Wales
Member 3	Leonardo Haruki Oguchi	Bachelor Course (3rd Year), Department of Electrical and Electronic Engineering, Faculty of Engineering, The University of Tokyo

2. Outline of the satellite (approx. 200 words)

Human spaceflight by non-professional astronauts has become increasingly popular in recent years. Many private companies are striving to make human spaceflight accessible for more people. However, risks are always present in human spaceflight, and fail-safe systems independent from the skills or knowledge of astronauts are necessary to lower the hurdle for human spaceflight. There are some escape procedures for ships and planes, but they heavily rely on the crews onboard. Spacecraft have much fewer people on board because of the limited payload mass; thus, sending experts to space every time is inefficient. Spacecraft autonomy has been increasing in recent years, but no space system is entirely safe; therefore, different approaches are needed to ensure passengers' safety.

We propose Space Lifeboat, which rescues another crewed spacecraft that lost its function to take passengers to earth safely. If a crewed spacecraft faces anomaly situations and using the capsule for reentry proves dangerous, Space Lifeboat transfers its orbit and rendezvous with the spacecraft. After docking and rescuing passengers, Space Lifeboat conducts reentry to earth. By having a fail-safe system outside of spacecraft, we can acquire a broader range of options to save passengers' lives, contributing to more reliable and sustainable human spaceflight in the future.

3. Aims and significance (Purpose, importance, technical or social significance etc)

(a) Aims

The primary objective of this mission is to rescue passengers from spacecraft that faced crucial problems in the vehicle and take them back home safely. The expected troubles or accidents of human spacecraft are as follows: collisions with space debris, oxygen tank leak, defect in ablation coating and so on. This mission also aims to improve the safety and reliability of human spaceflight and make human spaceflight available to more people. This mission requires highly ambitious technologies including fuel storage, arbitrary orbit transfer and rendezvous and docking with uncooperative targets; therefore developing technologies to achieve this mission is also an extremely important purpose.

(b) Importance, technical or social significance

This mission's most evident and essential benefit is saving passengers' lives and safely taking them home. Any accident in space leaves sadness beyond description to the passengers' family, friends, and more; therefore, preventing casualty by having a reliable backup is extremely important in future spaceflight. Furthermore, the importance of fail-safe systems for human spaceflight has been increasing recently because private companies all over the world are planning to send more people to space.

If more Space Lifeboats are launched to various orbits, a more comprehensive range of orbits will be covered and the time needed for rendezvous and docking decreases. The necessary time for rescue is crucial because life-support resources are limited and can be damaged in emergencies.

From a technical aspect, this is overall a very ambitious mission, and the whole space industries benefit from the outcome of this mission. There are three leading vital technologies to be developed to realize this mission: rendezvous and docking with uncooperative objects, arbitrary orbit transfer, and fuel and life-support system storage in space. They all have a wide range of usage in the future space business. Orbit transfer loosens the constraints for launch vehicle selection and increases the flexibility of the missions. Reliable rendezvous and docking technologies enable space debris collection and delivery systems among spacecraft.

Furthermore, storing fuel and life-support systems for a long time is essential in establishing infrastructures on the moon or Mars in the future because the frequency of supply from the earth is limited due to its cost and distance. There are a lot more usages for these techniques as well. Demonstrating these technologies in a single mission undoubtedly contributes to future space development.

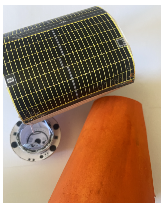
4. Specific content of the Mission

(a) System (overall configuration, shape, mass, function, orbit, data acquisition etc, including ground station and satellite/mission device)

Orbit	Orbit in a Nominal Situation: 580 km, circular, 45° inclination; Service Range: ±10° inclination angle change 200 km ~ 580 km altitude	Wet Mass	~ 7500 kg
Dimensions	Diameter: 4 m; Height: 4 m;	Propulsion	18×NTO / MMH thrusters (Isp = 300s, Thrust 400N)
Payload	Human-rated re-entry capsule; 6 passenger capacity; Life Support for 432 Human-hours; IDSS standard docking mechanism	ADCS	Thrusters; Lidar; Cameras; IMU; Star trackers; GPS
Structure	Pressurized volume:$7.5 m^3$ Unpressurized volume:$14 m^3$	Communication	Telemetry and video transmitters in S-Band Uplink: 300kbps; Downlink: >300Mbps
Ground Station	Tracking and Data Relay Satellite System	C&DH	On-board compression and encryption/decryption systems; Flight Computers
Thermal Control	Fluid cooling loops and radiator inside of the structure Heat shield: PICA-X	Electrical Power	Space Solar Cells; Lithium-ion batteries

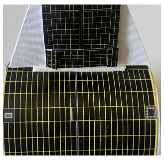
Space Lifeboat Configuration and Specifications

(b) Concrete achievement methods or necessary tasks and/or items to be developed



Space Lifeboat is launched by an H2A rocket or rockets with a similar launch capability to H2A, which can lift a 7.0-ton payload to the intended orbit.

After being released from the launch vehicle, it conducts some trajectory correction and stays at 580 km in altitude and 45 deg inclination angle until another spacecraft needs Space Lifeboat. While waiting in orbit, it consumes some fuel to keep its altitude.



If a crewed spacecraft faces a critical problem, Space Lifeboat waits in the current orbit so that it can synchronize with the spacecraft. After finding a proper trajectory, it burns its fuel to change the inclination angle and altitude. The spacecraft solves a Lambert problem to search for the best trajectory to reach the target spacecraft efficiently. Orbit transfer is followed by rendezvous and docking. Rendezvous and docking has four stages: orbit change; relative approach; final approach; docking. Before relative approach, the space lifeboat uses its absolute GPS position and the ground station monitoring to stay on the right trajectory. In the relative approach, it uses the relative GPS from the target spacecraft and utilizes the C-W navigation. When it docks with the spacecraft, it needs to revolve around the spacecraft at the same angular speed on the same plane as the spacecraft's rotation; therefore, the Space lifeboat uses its thrusters to change the rotation rate and points its docking system to the spacecraft's one. Docking is conducted using cameras and lidar. Using magnetic power at the end of docking makes the docking more reliable. Orbit change, rendezvous and docking can be done in several hours, and the necessary time for rescue would dramatically decrease if there are multiple space lifeboats in orbit, shown in our simulation. Therefore, this mission aims to be the technology demonstration mission, and launch more space lifeboats in the future to expand the service range and increase the reliability. After docking with the spacecraft, it decelerates the spacecraft's spin for passengers' safety. Moving passengers to Space Lifeboat is followed by undocking with the spacecraft, orbit change, and reentry burns to go back to earth. Finally, Space Lifeboat deploys its parachute and splashdown in the ocean, where passengers can be rescued in a short time.

There are also serious problems related to Life Support Systems. Almost all the human-rated spacecraft have sustainable Life Support Systems, for example the Environmental Control and Life Support System(ECLSS), but considering the long waiting time before an accident happens, sustainable systems are not required for this mission, and in order to reduce electricity consumption and payload mass, oxygen cylinder and water tank instead of oxygen generator and water recovery system.

5. Originality and/or social effects

(a) Originality of the mission

The idea of a “space lifeboat” exists in ISS, where the Soyuz spacecraft are used for emergency escapes. However, utilizing spacecraft in a different orbit to rescue another spacecraft has never been proposed. Also, rendezvous and docking with uncooperative targets have been studied widely, but the use of that technology for crewed spacecraft is particularly ambitious and unique. Orbit transfer to random orbits at an arbitrary time is not a standard technology, so we investigated its feasibility from scratch. This mission requires storing life-support systems and fuels for a long period of time, which has not been done widely in space missions; therefore, we investigated the feasibility of storage of air, fuel, food and so on.

(b) Anticipated results, effects, intended users

This new fail-safe system makes space travel available to more people for two reasons. Firstly, the passengers need less training and preparation for emergencies before spaceflight because the rescue procedures are done autonomously. Secondly, having another backup vehicle to rescue them mitigates fear and nervousness associated with risky spaceflight; therefore, more people are expected to get interested in spaceflight, which activates the space industry and business. Increasing the popularity of human spaceflight in the world is very important because money from the public is a vital fuel to achieve sustainable space development.

Space Lifeboat

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Abstract

Space Lifeboat, a mission to save passengers' lives under emergency situations is proposed. Due to commercialization of space travel, human spaceflight by non-professional astronauts is estimated to radically increase in the near future. Accordingly, the risk of having accidents in space will be increased. To save passengers' lives, this lifeboat usually stays in orbit at an altitude of 580 km, and when an accident happens, heads to and docks a spacecraft which has a problem, provides a life support system, and separates a capsule and the capsule re-entries to the earth. The area covered by this space lifeboat is limited by propellant capacity , but just as the first step for safe space travels, this mission will contribute to the future.

Introduction

Human spaceflight by non-professional astronauts has become increasingly popular in recent years. Many private companies are striving to make human spaceflight accessible for more people. However, risks are always present in human spaceflight, and fail-safe systems independent of the skills or knowledge of astronauts are necessary to make human spaceflight accessible to the public. Currently, there are some escape procedures for ships and aircraft have some emergency procedures (including evacuation), but they heavily rely on the crews onboard. Spacecraft have fewer people on board because of the limited payload mass; thus, sending experts to space every time is inefficient. Spacecraft autonomy has been increasing in recent years, but no space system is entirely safe; therefore, different approaches are needed to ensure passengers' safety.

We propose Space Lifeboat, which can rescue another crewed spacecraft that has lost functionality to return passengers to Earth safely. If a crewed spacecraft faces an anomalous situation and using the capsule for reentry proves dangerous, the Space Lifeboat transfers its orbit and rendezvous with the spacecraft. After docking and rescuing passengers, the Space Lifeboat performs a safe reentry. By having a fail-safe system outside of the spacecraft, we can acquire additional, redundant options to save passengers' lives, contributing to more reliable and sustainable human spaceflight in the future.

1. Mission Aims and Purposes

1.1 Aims

The primary objective of this mission is to rescue passengers from spacecraft that faced crucial problems in the vehicle and take them back home safely. Possible human spacecraft incidents or accidents include: collisions with space debris, oxygen tank leak, defect in ablation coating and so on. This mission also aims to improve the safety and reliability of human spaceflight and make human spaceflight available to more people. This mission requires highly ambitious technologies including fuel storage, arbitrary orbit transfer and rendezvous and docking with uncooperative targets; therefore developing technologies to achieve this mission is also an extremely important goal.

1.2 Technical and Social Significance

This mission's most evident and essential benefit is saving passengers' lives and safely returning them home. Any accident in space leaves sadness beyond description to the passengers' family, friends, and more; therefore, preventing casualty by having a reliable backup is extremely important in future spaceflight. Furthermore, the importance of fail-safe systems for human spaceflight has been increasing recently because private companies all over the world are planning to send more people to space.

If more Space Lifeboats are launched to various orbits, a more comprehensive range of orbits will be covered and the time needed for rendezvous and docking decreases. The necessary time for rescue is crucial because life-support resources are limited and can be damaged in emergencies.

From a technical aspect, this is overall a very ambitious mission, and the whole space industries benefit from the outcome of this mission. There are three leading vital technologies to be developed to realize this mission: rendezvous and docking with uncooperative objects, arbitrary orbit transfer, and fuel and life-support system storage in space. They all have a wide range of usage in the future space business. Orbit transfer loosens the constraints for launch vehicle selection and increases the flexibility of the missions. Reliable rendezvous and docking technologies enable space debris collection and delivery systems among spacecraft.

Furthermore, storing fuel and life-support systems for a long time is essential in establishing infrastructures on the moon or Mars in the future because the frequency of supply from the earth is limited due to its cost and distance. There are a lot more usages for these techniques as well. Demonstrating these technologies in a single mission undoubtedly contributes to future space development.

2. Mission

2.1 Mission Architecture

2.1.1 Orbit

Space Lifeboat's orbit is a circular orbit with an altitude of 580 km and inclination angle of 45 degrees. This orbit was chosen for several reasons. Firstly, the altitude of 580 km is enough to cover most of the crewed spacecraft in orbit, and enough weight can be lifted to this altitude by rockets such as H2A rockets. H2A rocket's payload capacity for 580 km altitude with 51-degree inclination angle is 7.0 t and 7.3 t for 580 km altitude with 30-degree inclination angle [15]; therefore we can assume that we can carry about 7.0 t, which is the maximum weight of a Space Lifeboat, to 45 degrees inclination angle.

Secondly, most crewed spacecraft are in an LEO orbit below 580 km and this altitude can cover most of the crewed spacecraft. For example, the ISS is at 408 km in altitude, and Space X's "Earth Orbit" mission plans to use an orbit with an altitude of 300 km.

Thirdly, many spacecraft use the inclination angle of from 35 to 55 degrees because of the launch site latitude, and ISS orbits at the inclination angle of 51.8 degrees, which implies covering from 35 to 55 degrees of the inclination angle is reasonable to cover as many spacecraft as possible with the same inclination angle range.

Fourthly, there are a lot of constellation satellites around 550 km and 600 km altitude, and 580 km is a safe altitude to stay for several years at most.

Finally, this inclination angle is also reasonable for the launch vehicle because the launch site, such as Tanegashima Space Center, is located around the latitude of 30 degrees, and it needs less fuel to launch the rocket to an orbit of 45 degrees than some other orbits like equatorial orbits.

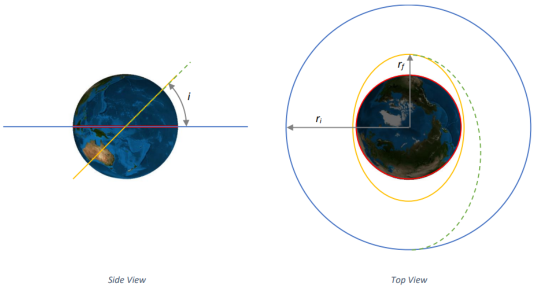
2.1.3 Orbit transfer

2.1.3.1 Delta-V using the Hohmann transfer

The Space Lifeboat uses orbit transfer to synchronize with the spacecraft in need. Less ΔV is required for inclination change in higher orbits; therefore, the spacecraft conducts an inclination angle change and orbit altitude change at 580 km altitude and transfer to the elliptical orbit. After that, the Space Lifeboat burns its fuel again to reach the final orbit for rendezvous and docking. To calculate Delta-V for this procedure, we made three assumptions as follows:

- Kepler motion
- Two-body problem
- Park and Final orbits are circular

The total delta V was calculated by the Hohmann transfer formulas, and we get $\Delta v = 1.36$km/s. The amount of fuel required for this orbit transfer is calculated in section 2.2.3.



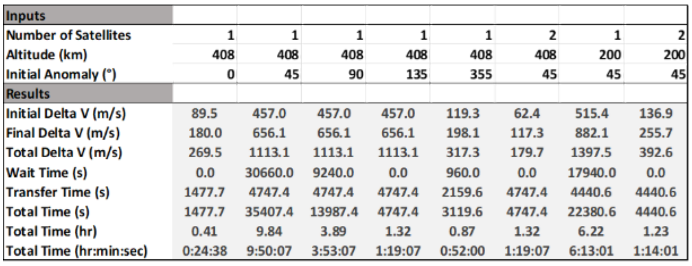
Side View

Top View

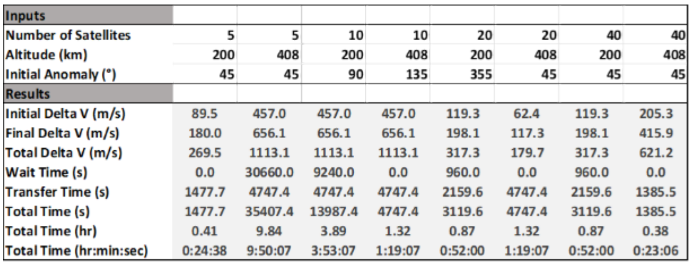
Side View/ Top View of the orbit transfer

2.1.3.2 Rescue time estimation

We used the Hohmann transfer to estimate the amount of propellants needed for the orbit change, but the waiting time of the spacecraft can be reduced by solving the Lambert problem. Assuming that the time for the inclination change is short enough, we created the simulation to optimize the orbit to minimize the total time to reach the target spacecraft which is on the same plane but different latitude and anomaly. In order to analyze the effect of the number of satellites on the waiting time and the total time for orbit transfer, we changed the number of satellites in orbit. If there is more than one interceptor, they are positioned at equidistant anomalies. We assumed that both target and interceptor spacecraft are initially in circular orbits. From section 2.2.3, we can estimate the

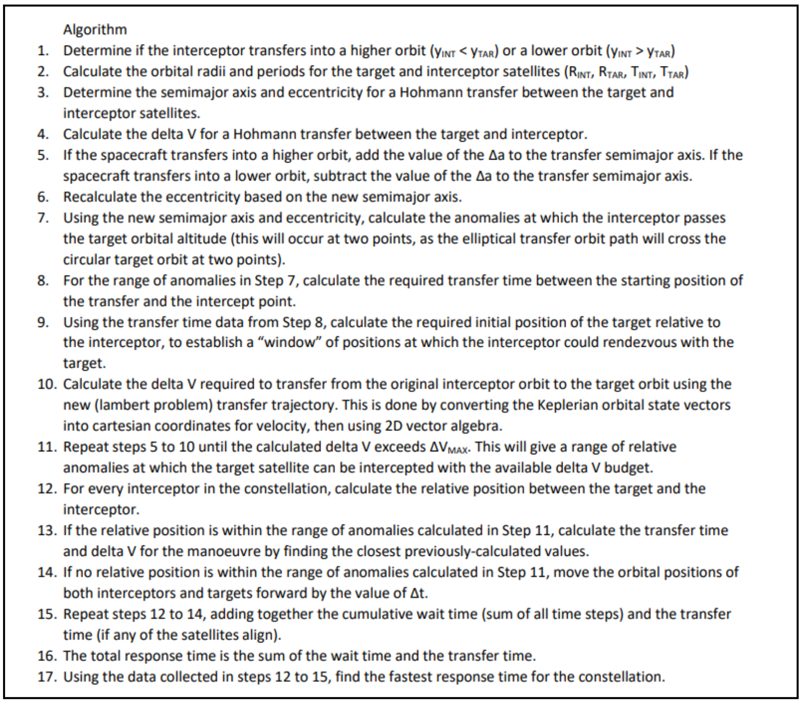


Inputs								
Number of Satellites	1	1	1	1	1	2	1	2
Altitude (km)	408	408	408	408	408	408	200	200
Initial Anomaly (°)	0	45	90	135	355	45	45	45
Results								
Initial Delta V (m/s)	89.5	457.0	457.0	457.0	119.3	62.4	515.4	136.9
Final Delta V (m/s)	180.0	656.1	656.1	656.1	198.1	117.3	882.1	255.7
Total Delta V (m/s)	269.5	1113.1	1113.1	1113.1	317.3	179.7	1397.5	392.6
Wait Time (s)	0.0	30660.0	9240.0	0.0	960.0	0.0	17940.0	0.0
Transfer Time (s)	1477.7	4747.4	4747.4	4747.4	2159.6	4747.4	4440.6	4440.6
Total Time (s)	1477.7	35407.4	13987.4	4747.4	3119.6	4747.4	22380.6	4440.6
Total Time (hr)	0.41	9.84	3.89	1.32	0.87	1.32	6.22	1.23
Total Time (hr:min:sec)	0:24:38	9:50:07	3:53:07	1:19:07	0:52:00	1:19:07	6:13:01	1:14:01



Inputs								
Number of Satellites	5	5	10	10	20	20	40	40
Altitude (km)	200	408	200	408	200	408	200	408
Initial Anomaly (°)	45	45	90	135	355	45	45	45
Results								
Initial Delta V (m/s)	89.5	457.0	457.0	457.0	119.3	62.4	119.3	205.3
Final Delta V (m/s)	180.0	656.1	656.1	656.1	198.1	117.3	198.1	415.9
Total Delta V (m/s)	269.5	1113.1	1113.1	1113.1	317.3	179.7	317.3	621.2
Wait Time (s)	0.0	30660.0	9240.0	0.0	960.0	0.0	960.0	0.0
Transfer Time (s)	1477.7	4747.4	4747.4	4747.4	2159.6	4747.4	2159.6	1385.5
Total Time (s)	1477.7	35407.4	13987.4	4747.4	3119.6	4747.4	3119.6	1385.5
Total Time (hr)	0.41	9.84	3.89	1.32	0.87	1.32	0.87	0.38
Total Time (hr:min:sec)	0:24:38	9:50:07	3:53:07	1:19:07	0:52:00	1:19:07	0:52:00	0:23:06

maximum mass of the propellant which can be used for the orbit change. By setting the maximum mass of the propellant to be 1.36 km/s, we get the tables on the right. These show that the necessary time for the orbit change is greatly affected by the initial anomaly between the space lifeboat and the target spacecraft and the number of satellites. Also, it tells us that having two satellites in the same orbit instead of one makes a great difference in total time for rescue, exemplified by the orbit change to 408 km altitude with 45-degree initial anomaly. The algorithm for the simulation is shown on the right.



Algorithm

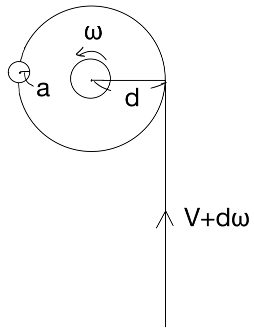
1. Determine if the interceptor transfers into a higher orbit ($y_{INT} < y_{TAR}$) or a lower orbit ($y_{INT} > y_{TAR}$)
2. Calculate the orbital radii and periods for the target and interceptor satellites (R_{INT}, R_{TAR}, T_{INT}, T_{TAR})
3. Determine the semimajor axis and eccentricity for a Hohmann transfer between the target and interceptor satellites.
4. Calculate the delta V for a Hohmann transfer between the target and interceptor.
5. If the spacecraft transfers into a higher orbit, add the value of the Δa to the transfer semimajor axis. If the spacecraft transfers into a lower orbit, subtract the value of the Δa to the transfer semimajor axis.
6. Recalculate the eccentricity based on the new semimajor axis.
7. Using the new semimajor axis and eccentricity, calculate the anomalies at which the interceptor passes the target orbital altitude (this will occur at two points, as the elliptical transfer orbit path will cross the circular target orbit at two points).
8. For the range of anomalies in Step 7, calculate the required transfer time between the starting position of the transfer and the intercept point.
9. Using the transfer time data from Step 8, calculate the required initial position of the target relative to the interceptor, to establish a "window" of positions at which the interceptor could rendezvous with the target.
10. Calculate the delta V required to transfer from the original interceptor orbit to the target orbit using the new (lambert problem) transfer trajectory. This is done by converting the Keplerian orbital state vectors into cartesian coordinates for velocity, then using 2D vector algebra.
11. Repeat steps 5 to 10 until the calculated delta V exceeds ΔV_{MAX}. This will give a range of relative anomalies at which the target satellite can be intercepted with the available delta V budget.
12. For every interceptor in the constellation, calculate the relative position between the target and the interceptor.
13. If the relative position is within the range of anomalies calculated in Step 11, calculate the transfer time and delta V for the manoeuvre by finding the closest previously-calculated values.
14. If no relative position is within the range of anomalies calculated in Step 11, move the orbital positions of both interceptors and targets forward by the value of Δt.
15. Repeat steps 12 to 14, adding together the cumulative wait time (sum of all time steps) and the transfer time (if any of the satellites align).
16. The total response time is the sum of the wait time and the transfer time.
17. Using the data collected in steps 12 to 15, find the fastest response time for the constellation.

2.1.4 Rendezvous and docking

Rendezvous and docking has four stages: orbit change (~500 m from the target); relative approach (~ 10 m from the target); final approach; docking. The space lifeboat uses its absolute GPS position and the ground station monitoring to change the orbit.. In the relative approach, it uses the relative GPS from the target spacecraft and utilizes the C-W navigation.

To dock with the target spacecraft, the relative velocity between the two docking systems must be zero. Therefore, if the target spacecraft is spinning, the Space Lifeboat needs to rotate around the target spacecraft before docking. Docking is conducted using cameras and lidar. Lidar captures the shape and the distance of the target satellite, and the camera tracks the key points of the docking system to know the relative position and angle of the spacecraft. Using magnetic power at the end of docking makes the docking more reliable. After docking with the spacecraft, it decelerates the spacecraft's spin for passengers' safety. Moving passengers to Space Lifeboat is followed by undocking with the spacecraft, orbit change, and reentry burns to go back to earth.

We roughly estimated how much rotation can be generated by the propulsion system and how much fuel will be used for this procedure. We think about a simple model like the figure on the right. The target spacecraft is spinning at the angular velocity ω, and the Space Lifeboat is rotating around it while pointing the docking port to the target spacecraft. This model is simple yet useful because the waiting spacecraft is supposed to turn off its propulsion system and rotate at the constant speed around the same axis. The movement of the Space Lifeboat can be separated into two kinds of movements: revolution and orientation. Revolution is achieved by the centripetal force generated by thrusters. The supported angular velocity of the target vehicle is decided by how much revolution can be created by the propulsion system of Space Lifeboat. When the revolution radius is $r = 3$m, the equation of motion is $F = mr\omega^2$, where m is the mass of the vehicle and F is the centripetal force. The value for r comes from the radius of SpaceX Crew Dragon's diameter (approx. 4m) plus some distance for rotation. Thus, accepted angular velocity of the target is calculated by Eq (9):



A simple model of rendezvous and docking

$$\omega_{max} = \sqrt{\frac{F}{mr}} \ldots(9)$$

If there are 10 thrusters for creating the centripetal force, $F = 10 \cdot 400 = 4000$N, $\omega_{max} = 0.444$ rad/s $= 25.6$ deg/s. If a SpaceX Crew Dragon is rotating at this speed, it generates the G-force calculated in Eq (10):

$$\frac{a_d \omega_{max}^2}{g} = 0.0403 \ldots(10)$$

where a_d is the radius of the vehicle, which means that passengers can stand the G-force at the edge of the service range of a Space Lifeboat. If it takes about 60 sec. to dock with the spacecraft, the consumed fuel mass is calculated by Eq (11):

$$\frac{60\cdot F}{gI_{sp}} = 81.6\ \text{kg}\ldots(11)$$

Orientation is the spin of the vehicle and it matches with the orientation of the target spacecraft. If the shape of the spacecraft is a cylinder with the radius a, the required impulse for creating this rotation is calculated by $I = ma\omega$, where m is the mass of the vehicle. By substituting $m = 6500\text{kg}$, $a = 2m$, $\omega = 0.444$, we get $I = 6000$ N·s. The value for a comes from the diameter of the vehicle. The thrust $F = 400$ N and $I_{sp} = \frac{F}{\dot{m}g}$=300s; therefore, the required mass of fuel m_f is calculated by Eq (12):

$$m_f = \dot{m}t = \frac{F}{gI_{sp}}\cdot\frac{I}{F} = \frac{I}{gI_{sp}} = 2.04\ \text{kg}\ldots(12)$$

which is relatively small compared to the size of the tank. As a result, the consumption of fuel during rendezvous and docking is about 100~200 kg.

2.1.5 Keeping the orbit

The spacecraft stays in orbit for many months and it needs some delta-V to keep its orbit. Here we calculate delta-V needed to keep the vehicle's orbit at 580 km in altitude.

We assumed the shape of the vehicle is a bullet, which has a drag coefficient of 0.295, according to [13].

We used the spreadsheet provided by [11]. It gives us the annual delta-V is 0.2387 m/s, which can be ignored compared with delta-V for orbit transfer.

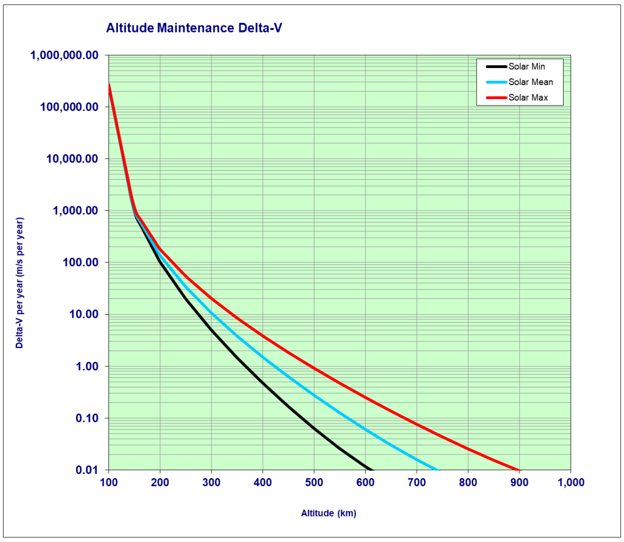
2.1.6 De-orbit burn

The Space Lifeboat is now orbiting around the earth, so it needs some propellants to decelerate the vehicle for reentry. After reentry, Space Lifeboat deploys its parachute and splashdown in the ocean, where passengers can be rescued in a short time.

According to [10], the SpaceX Crew Dragon used four engines to slow down, and the deorbit burn lasted for 11 and a half minutes. The amount of propellants used for this procedure can be calculated in the same way as 2.1.4.:

$$m_{propellants} = \frac{Ft}{gI_{sp}} = 3.75\cdot 10^2\ \text{kg},,.(13)$$

where $F = 4\cdot 400 = 1600\text{N}$, $I_{sp} = 300\text{s}$. This value varies according to the altitude of the target spacecraft and the splashdown location.



Attitude Maintenance delta-V

2.2 Spacecraft System Architecture

2.2.1 Payload

Our mission of Space LifeBoat can be mainly divided into 3 sections; rendezvous and docking, Life Support, re-entry to the earth. Considering the regulation of weight which can be launched by H-2A, the capacity of the spacecraft was set to 3 days and 6 crew during calculation.

2.2.1.1 Life Support System

As a Life Support System (LSS), environmental monitoring, atmosphere management, and water management need to be considered [1]. One of the good examples of LSS is the Environmental Control and Life Support System (ECLSS) in the International Space Station developed by NASA. This System was designed for long-term missions, automation and sustainability were highly important, but our mission is focused on emergent situations and a short-term mission, so those points don't have to be considered seriously.

2.2.1.1 Environmental Monitoring

a) Pressure control

As for pressure control, there are mainly 2 requested functions; monitoring pressure, and adjusting its inner pressure to around 1 atm. To monitor pressure inside of the spacecraft, a pressure gauge is necessary, and this gauge is provided with power by EPS. The amount of nitrogen required for pressure control will be explained later with that of oxygen.

b) Temperature control

This topic is highly related to thermal control, so detail will be analyzed in section 2.2.2.1. As payload, a thermos-hygrometer is needed and the weight is about 135[g], and this power is provided from EPS, but it is not so large.

c) Humidity control

Amount of insensitive evaporation of a normal healthy man in calm condition at normal temperature is about 900[ml] per day (from skin about 600[ml], from breath about 300[ml])[2]. This number does not include sweat because the amount of sweat is strongly influenced by surrounding environmental conditions, so further consideration is needed, but this time, we estimated that humans sweat 2[L/day]. So, the dehumidifier has to remove about 3[L/day] per person. Thinking about using a typical industrial dehumidifier, the capacity is 64.2[L/day], its weight is 25.4[kg], and coefficient of performance is 2.27[L/kWh][3]. Based on these specifications, the weight of the dehumidifier will be about 7.1[kg] and required power will be about 329.4[W].

2.2.1.2 Atmosphere Management

Oxygen supply, carbon dioxide removal, and pressurization with nitrogen are the biggest problems when thinking about manned space flight missions.

Firstly, about oxygen supply, considering weight and electricity consumption, an oxygen cylinder will suit this mission instead of using an oxygen generator. A normal healthy man consumes 0.5~0.6L oxygen in 1 atm per 1 minute [4].

$$0.6[L/min]\times 60[min]\times 24[hour]\times 3[days]\times 6[person] = 15552[L]$$

This weighs about 20[kg], and in 2200 PSIG (maximum pressure of oxygen cylinder), the volume is about 102[L]. a 47L type cylinder weighs about 53[kg], so a 60L type cylinder is estimated to weigh about 68[kg]. So, the total weight related to oxygen supply is about 156[kg].

Secondly, thinking about carbon dioxide removal, we decided to use a CO2 scrubber[7]. The canister is completely filled with the soda lime, the soda lime has to be changed every 6 hours. From the data sheet, the total weight for 3 days is 151[kg].

Lastly, nitrogen pressurization is discussed. The volume of this space lifeboat is estimated as large as a station wagon, about 7530 [L] and this amount of nitrogen weighs about 8.6[kg]. If nitrogen gas is compressed at 200 [bar], the volume becomes 38[L]. If we use a 47 L steel cylinder, its weight is about 53[kg], so the total weight of nitrogen and cylinder is 61.6[kg].

2.2.1.3 Water Management

A person needs to drink 1.5[L] of water per day. So, at least 27[L] of water has to be supplied for 6 crew and 3 days. Thinking about bringing 30[L] of water, it weighs 30[kg].

2.2.1.4 Seating System

When considering the seating system, seats for racing cars are a good reference. One example of the seats shows that its weight is 20 pounds (about 9.1[kg]), so 6 seats weigh about 55 [kg].

2.2.1.5 Docking System

The ***International Docking System Standard*** (IDSS) docking mechanism, the most widely used one, should be used for this space lifeboat, and an adapter for the International Docking System weighs about 526[kg].

2.2.1.6 Re-entry System

Parachute landing is our solution to re-entry. As Dragon, 2 drogue parachutes and 4 main parachutes are equipped. From the data sheet of Orion's parachute system, these parachutes weigh 630[kg] in total.

2.2.2 Thermal protection and control

2.2.2.1 Thermal control in space

In this part, thermal control during going around the earth before re-entry is discussed. Operation temperature is set to 10-46[℃] and average temperature is set to T = 20[℃] When 6 crew members are in the space lifeboat, 100[W] heat is emitted from one person[9], so 600[W] is emitted from crew members.So, heat from the system (Q_{sys}) can be estimated to 600[W].

Environmental heat flow is calculated by Eq (14): $Q_{env} = \alpha S(A_s + RA_p) + \varepsilon I A_p$…(14)

where Q_{env} is the environmental heat flow, α is the surface absorptivity, S is the solar flux, A_s is the sun-facing projected area, R is percentage of solar flux reflected by the planet, A_p is the planet-facing projected area, and I is infra-red radiation flux. Z-93C55 is used for the surface painting and this material shows α = 0.17 - 0.20, ε = 0.92. Also, from the bus design, $A_s = A_p = 4 \times 4 + 4(2 + \sqrt{3}) = 30.92[m^2]$

R = 0.37, I = 231, S = 1365 are also given, from the data above, $Q_{env} = 1.73 \times 10^5$[W]

Next, heat flow out of spacecraft is calculated by Eq (15): $Q_{out} = \Sigma[A_{Ri}\varepsilon_i]\sigma T^4$…(15)

where $A_R = 199.3[m^2]$, so $Q_{out} = 7.66 \times 10^5$[W]. To keep the temperature stable, heater or a water loop system is required

2.2.2.2 Thermal protection during re-entry

The capsule was protected by a heat shield made from PICA-X which can withstand up to 1600[℃].

2.2.3 Propulsion system

2.2.3.1 Propulsion Subsystem

In this mission, supposing a sufficiently high specific impulse, the storage capacity of the propulsion system is firstly given in consideration. In addition, there is the requirement for high controllability, due to the movement required during orbit entry and re-entry. Thus, a hypergolic liquid rocket propulsion was selected for this mission, given that it has high storability, and it is ideal for missions that require precise controls of the spacecraft.

A COTS propulsion system has been selected. The Draco engine (SpaceX) can provide sufficient specific impulse (300s) with maximum fuel capacity of 1,290kg. The engine generates a thrust of 400N, operating by 2 solar arrays around 1500W-2000W. Also, the propellant used in this engine is MMH/NTO.

Assuming an orbital altitude of 500 km, it was calculated that the maximum delta-v budget required for the orbital maneuvering is 6.45 m/s. Using the Tsiolkovsky rocket equation,

$$m_{propellants} = m_{dry}(\exp(\frac{\Delta V}{g I_{sp}} - 1)\ldots(16)$$

where $m_{propellants}$ is the required mass of propellants and m_{dry} is the dry mass of the vehicle. By substituting $m_{dry} = 4000$ kg, I_{sp}=300s, we get $m_{propellants} = 2.49 \cdot 10^3$kg. By adding required propellants for rendezvous and docking, and reentry, total mass of propellants will be $2.79 \sim 2.89 \cdot 10^3$kg. Thus, the wet mass of the vehicle is $6.79 \sim 6.89$ t. However, we haven't calculated these figures with the actual trajectories being used and we haven't quantified the increased mass of the tanks; therefore, we have 110 kg ~ 210 kg margin for payload wet mass, which is enough to cover those values.

2.2.4 Attitude Determination and Control Subsystem

For the general attitude determination, Inertial Measurement Unit (IMU) and star trackers are used. On the other hand, when Space Lifeboat docks with other spacecraft, cameras and lidars are also used to know the relative distance and position of the vehicle from the target. 18 thrusters similar to SpaceX Draco thrusters are used to change the attitude, transfer the orbit, and deorbit.

2.2.5 Communication Subsystem

This part follows the newest crewed spacecraft demonstrated in orbit, SpaceX Crew Dragon, which supports communications via satellites and Ground Stations on Earth [14]. Data rates are 300kbps for command uplink and 300Mbps or more for telemetry and data downlink. Vehicle communications are conducted via redundant telemetry and video transmitters in S-Band.

2.2.6 Command and Data Handling Subsystem

Space Lifeboat has compression and encryption/decryption systems on board. Flight Computers provide all essential functions of vehicle control and navigation. It uses image recognition algorithms and a lidar to detect and localize the docking system of the target spacecraft, and based on the 3-D position and the angle of the docking station, the flight computers send proper signals to the thrusters.

2.2.7 Electrical Power Subsystem

The electronic system was elaborated to attend all the systems required by the mission. COTS will be taken into consideration in the EPS schematization.

In power generation, ZTJ-Ω Space Solar Cell will be used as the power source. Such a solar panel has a minimum average BOL performance of 30.2%, and its power generation rate at 28°C is 135.3 mW/cm2. To satisfy the 2000W requirement during the mission, 185 units of an 80cm2 cell will be needed, covering a total of 1.48 m2. This is a compatible size in relation to the spacecraft size.

The battery used in this mission is the VL51ES battery. Lithium-ion batteries have the advantage of being more compact, and the VL51ES reaches battery specific energy superior to 130Wh/kg, which is sufficient for the mission.

2.3 Development Tasks and Issues

This mission requires many advanced techniques that haven't been demonstrated in reality. For example, rendezvous docking with uncooperative crewed spacecraft requires high reliability of algorithms, sensors and actuators. This is not only an extremely difficult task, but also hard to practice because there are crews in the spacecraft. Practicing the maneuver for rendezvous and docking with uncrewed spacecraft many times is required before using it for crewed spacecraft.

Orbit synchronization is another problem especially when the spacecraft is in a higher orbit where there is less orbit period difference. A Space Lifeboat needs to rescue the passengers within several days because the life-support systems of the spacecraft don't last for a long time especially when the vehicle faces critical problems. We haven't developed how to calculate the optimal trajectory to rendezvous with the target spacecraft, so this part should be developed by the hands of orbital mechanics.

The amount of propellant required for rendezvous and docking was calculated with a very simple model; therefore, we haven't taken into account the transition between the circular orbit and the rendezvous trajectory. The algorithms of rendezvous and docking should be developed to increase the reliability and efficiency of the maneuver.

Anticipated Results

This new fail-safe system makes space travel available to more people for two reasons. Firstly, the passengers need less training and preparation for emergencies before spaceflight because the rescue procedures are done autonomously. Secondly, having another backup vehicle to rescue them mitigates fear and nervousness associated with risky spaceflight; therefore, more people are expected to get interested in spaceflight, which activates the space industry and business. Increasing the popularity of human spaceflight in the world is very important because money from the public is a vital fuel to achieve sustainable space development.

Originality and Social Effects

The idea of a “space lifeboat” exists in ISS, where the Soyuz spacecraft are used for emergency escapes. However, utilizing spacecraft in a different orbit to rescue another spacecraft has never been proposed. Also, rendezvous and docking with uncooperative targets have been studied widely, but the use of that technology for crewed spacecraft is particularly ambitious and unique. Orbit transfer to random orbits at an arbitrary time is not a standard technology, so we investigated its feasibility from scratch. This mission requires storing life-support systems and fuels for a long period of time, which has not been done widely in space missions; therefore, we investigated the feasibility of storage of air, fuel, food and so on.

References

[1] web page about ECLSS from NASA homepage:
https://www.nasa.gov/content/life-support-systems

[2] evaporation from human body:
https://www.kango-roo.com/learning/2575/

[3] One example of industrial dehumidifier:
https://www.alorair.com/product-details/alorair-sentinel-hd55blue

[4] Stephan A. Loer, MD; Thomas W. L. Scheeren, MD; Jorg Tarnow, MD, FRCA, *How Much Oxygen Does the Human Lung Consume?*,March 1997
https://doi.org/10.1097/00000542-199703000-00004

[5] One example of carbon dioxide analyzer:
https://www.labcompare.com/503-Carbon-Dioxide-Analyzer-CO2-Gas-Analyzer/17014421-Carbon-Dioxide-Meter-PCE-CMM-10/?pda=503|17014421_8_0|||

[6] *Dragon-Cargo Version*:
https://spaceflight101.com/spacecraft/dragon/

[7] Comanex, *CO_2 SCRUBBER OPERATING MANUAL*,
https://spaceflight101.com/spacecraft/dragon/

[8] National Aeronautics and Space Administration, SpaceX CRS-7 Seventh Commercial Resupply Services Flight to the International Space Station,
https://www.nasa.gov/sites/default/files/atoms/files/spacex_crs7_mission_overview

[9] Human heat emission:
https://www.swissinfo.ch/eng/tecnologia_when-the-human-body-becomes-a-powerhouse/46547152

[10] Crew-2: Crew Dragon Deorbit Burn Complete
https://blogs.nasa.gov/commercialcrew/2020/08/02/deorbit-burn-underway-engine-firing-to-start-crew-dragons-descent/

[11] New SMAD
http://www.sme-smad.com/

[12] White Coating of Dragon
https://www.nasa.gov/mission_pages/station/research/news/dragon_coating

[13] Shape Effects on Drag
https://www.grc.nasa.gov/www/k-12/airplane/shaped.html

[14] Dragon Cargo Version
https://spaceflight101.com/spacecraft/dragon/

[15] H-IIA User’s Manual
https://www.mhi.com/jp/products/pdf/manual.pdf