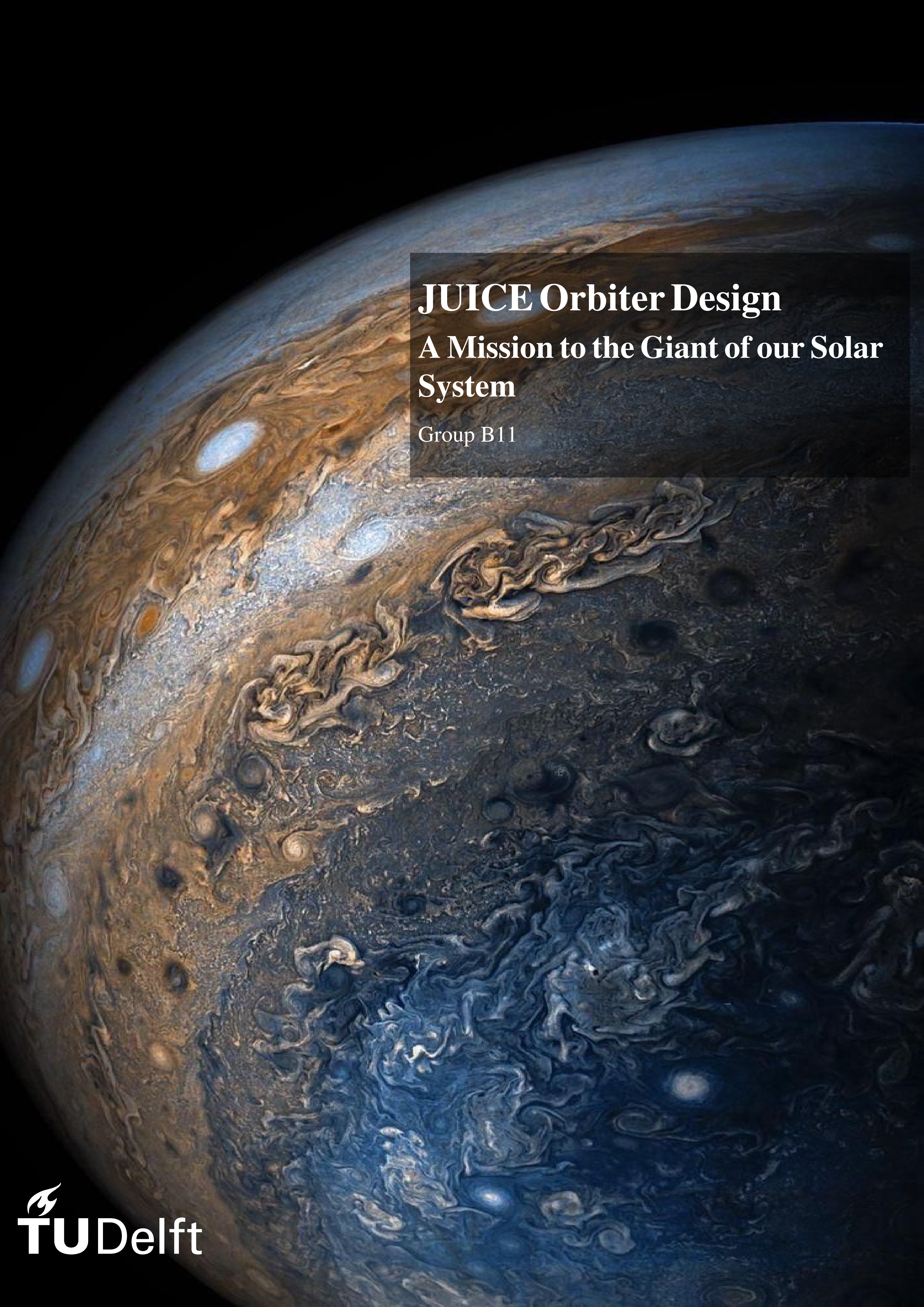
JUICE Orbiter Design

A Mission to the Giant of our Solar System

Group B11



TU Delft

DELFT UNIVERSITY OF TECHNOLOGY

FACULTY OF AEROSPACE ENGINEERING

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AEROSPACE SYSTEMS DESIGN

Design of the JUICE Spacecraft

A Mission to the Giant of our Solar System

Mission: Jupiter's JUICE mission
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Abstract

The study presented in this report focused on the detailed design of the solar panel attachment to the main bus of the spacecraft. A proper design of such structure is essential for the mission success, as any failure of the attachment would directly result in the loss of the primary source of power generation. The design is made through the determination of the loads that the attachment will endure during the complete mission, followed by the generation of the lug design and the selection of the fastener pattern. The design is then iterated on through a procedure taking into account the bearing stress in the fasteners, the push/pull through failure modes, thermal checks, and stresses induced by bending and normal loads. The iteration is continued until an efficient non-failing design is found. Finally, a material trade-off is performed and a CATIA drawing of the final design of the attachment is provided.

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Summary

When designing a spacecraft, even the failure of a small part can compromise the outcome of the mission. Therefore, it is of paramount importance to carefully design each part so that it is able to sustain the forces and moments, which will act on it during the mission. In this report, the process for the design of a lug attachment for the solar panels is described. For the solar panel of JUICE to be correctly deployed and to remain as such, the lug needs to sustain different types of loads and moments. Therefore, the first step is to determine the loads that act on it. The load analysis determined two different types: the launch ones and the loads due to the ADCS rotating the spacecraft. The loads and moments found are summarized in Table 1.

Table 1: Summary of forces and moments acting on the lug

Load type	F_x **[N]**	F_y **[N]**	F_z **[N]**	M_x **[Nm]**	M_y **[Nm]**	M_z **[Nm]**
Launch Loads	1643.2	1643.2	4929.5	295.8	2464.8	98.6
ADCS Loads	5.3	$454.14 \cdot \omega^2$	7.0	34.7	0.5	29.0

In the second part of the report, the lug attachment was designed. After comparing the two options available, a double lug configuration was chosen along with a rotating single lug for the deployment of the solar panels. This configuration is capable of sustaining a bending moment of $95.6\ Nm$ at maximum. Then, the dimensions for the lug were determined using an analysis approach from Bruhn[1] for an initial design and was repeated after the iterations. Since the lug configuration needs to be attached to the wall of the spacecraft, the fasteners were designed as well. Given that the number of fasteners, their width, length and spacing need to be determined, there are different designs possible. Three designs were generated, and each one of them was iterated further: using a python script the previously obtained designs were checked for bearing stress, push/pull failure and thermal stresses. If the chosen design was not able to sustain the given loads, the dimensions were altered and the procedure was performed again. After numerous iterations, the final geometry could be determined for two different lug materials: Aluminum 2043-T3 and Titanium Ti-6Al-4V (while the fasteners are made of Titanium Ti-6Al-4V for both designs). Those geometries essentially provide two different designs that were compared to each other using a trade off, from which the former was determined as the most appropriate one. The lug attachment will be made of Aluminum 2043-T3, while Titanium Ti-6Al-4V will be used for the fasteners. The dimensions of the attachment are listed in Table 2. A CATIA model of the final selected design is presented below in Figure 1.

Table 2: Geometrical properties of the attachment (see Figure 3.7)

Geometry	**Value [mm]**
w	97.75
D_1	58.78
D_2	8.81
t_1	4
t_2	0.5
t_3	1.35

Figure 1: Final design CATIA rendering

Contents

List of Symbols

Latin Letters	Quantity	Symbol Unit
A	Area	m^2
A_b	Area of the bolt	m^2
A_{br}	Net shear-bearing area	m^2
A_{shear}	Shear area	m^2
A_t	Net tension area	m^2
d	Diameter	m
D_1	Inner diameter of the lug	m
D_2	Inner diameter of the fastener	m
D_{fo}	Head diameter of the fastener	m
e_2	Distance center fastener to edge	m
E_a	Young's modulus of the attachment	N/m^2 or Pa
E_b	Young's modulus of the bolt	N/m^2 or Pa
F_{cgx}	X-component of the resultant force acting through the center of gravity	N
F_{cgz}	Z-component of the resultant force acting through the center of gravity	N
F_{ip-x}	In plane force from F_x	N
F_{ip-z}	In plane force from F_z	N
F_{ip-M_y}	In plane force from M_y	Nm
F_{tu}	Ultimate tensile strength of a material	N/m^2 or Pa
F_x	Force in X-direction	N
F_y	Force in Y-direction	N
F_z	Force in Z-direction	N
g	Gravity	m/s^2
h	Lug spacing	m
I_G	Moment of inertia about the center of gravity	$kg \cdot m^2$
m	Mass	kg
I_{xx}	Moment of inertia about the X-axis	$kg \cdot m^2$
I_{yy}	Moment of inertia about the Y-axis	$kg \cdot m^2$
I_{zz}	Moment of inertia about the Z-axis	$kg \cdot m^2$
k		
K_{bry}	Shear-bearing yield efficiency factor	[-]
K_t	Stress concentration factor	[-]
m	Mass	kg
M_G	Moment caused in the center of gravity	$N \cdot m$
M_{cgx}	Moment caused in the X-direction on the cg of the fasteners	$N \cdot m$
M_{cgy}	Moment caused in the Y-direction on the cg of the fasteners	$N \cdot m$
M_{cgz}	Moment caused in the Z-direction on the cg of the fasteners	$N \cdot m$
M_x	Moment caused in the X-direction	$N \cdot m$
M_y	Moment caused in the Y-direction	$N \cdot m$
M_z	Moment caused in the Z-direction	$N \cdot m$
MS	Margin of safety	[-]

n_f	Number of fasteners	[-]
P	Net force in Y/Z-plane	N
r	Radius	m
t_1	Thickness of the lug	m
t_2	Thickness of the fastener plate	m
t_3	Thickness of the Spacecraft wall	m
w	Width of the lug	m
W	Weight	kg
x_{cg}	X-position of the center of gravity	m
y_1	Distance between D_1 and fastener back up plate	m
z_{cg}	Z-position of the center of gravity	m

Greek Letters	**Quantity**	**Symbol Unit**
α	Angular acceleration	rad/s
α_c	Thermal expansion coefficient of component	[-]
α_b	Thermal expansion coefficient of fastener	[-]
δ_a	Compliance of the attachment	[-]
δ_b	Compliance of the bolt	[-]
Δ_T	Temperature difference	K
η	Efficiency	[-]
θ	Angle	deg
μ	Standard gravitational parameter	km^3/s^2
ρ_r	Reflectivity	[-]
σ	Boltzmann constant	[-]
$\sigma_b r$	Bearing stress	N/m^2 or Pa
τ	Maximum torque	$N \cdot m$
τ_2	Shear stress in the lug wall	Pa
τ_3	Shear stress in the Spacecraft wall	Pa
Φ	Force ratio	[-]
ω	angular velocity	rad/s

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ADCS - *Attitude Determination and Control System*
cg - *Center of gravity*
MS - *Margin of Safety*
eg - *example*

1 Introduction

During a space mission, several loads act on the spacecraft. Those are either external or generated by moving parts from the spacecraft itself. To assure the success of the mission, it is of critical significance to design every component of the spacecraft's structure, to sustain the loads that are applied to it. Even the failure of a small part can compromise the outcome of the whole mission.

Therefore, the goal of this report is to describe the detailed design of a small component of the spacecraft's structure, namely a lug attachment for the solar panels used on board of JUICE-orbiter. First, the loads that will be acting on the attachment need to be determined. Subsequently, the dimensions of the lug such as the thickness, the width and the fastener dimensions can be defined, using a design analysis from literature. Furthermore, the type of fastener to be used to attach the lug to the bus is identified, and will be checked for bearing and pull-through failure. Finally, the material for the lug will be chosen and a CATIA drawing of the attachment will be generated.

The structure of the report is the following: in chapter 2 the different types of loads acting on the attachment are determined, namely launch loads, thermal loads and dynamic loads. Moreover, the chosen lug configuration will be discussed in detail. In chapter 3, the design of the attachment is described: the process used to define the dimensions will be explained first, then the fasteners design will be described along with the different types of failures that can occur. In the end, the choice for the material will be discussed,

Load Determination 2

This chapter aims to determine the magnitude and direction of the loads acting on the attachment between the solar array and the vehicle wall. In section 2.1 the axis system is defined. In section 2.2 the loads during the launch phase are determined. Thirdly, in section 2.3 the loads carried by the connection during ADCS manoeuvres are determined. Finally, in section 2.4 the loads are summarized.

2.1 Axis system

Before starting with the determination of the loads, a common axis system used for all calculations is chosen. The axis system used in this report is shown in Figure 2.1

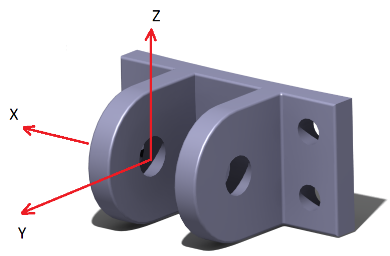
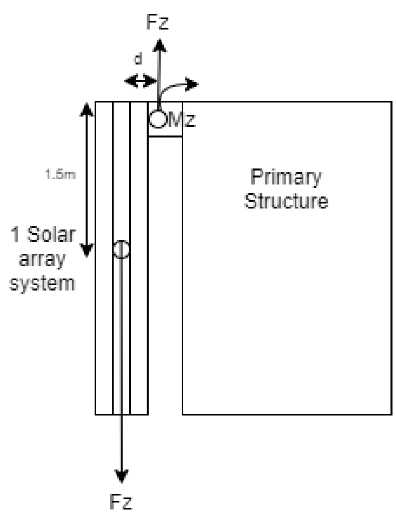


Figure 2.1: Overview of the axis system

2.2 Launch loads

During the launch phase, the lug connection will experience the most intense loads. Large accelerations cause a force in the Z-axis of the wall of the spacecraft, and a moment in the X-axis, these forces are represented by the figure 2.2.

Figure 2.2: Forces and moments in the Z-axis



The force F_z represented in the figure 2.2 is caused by the mass of the solar array system, this is supplemented by a force F_x, which is perpendicular to the force F_z. The forces F_z and F_x are maximum, when the launch loads of the spacecraft are at their maximum (statically and dynamically). Therefore, when taking into account the maximum loading, the load in the Z-direction is taken to be $6g$, while $2g$ is used in the X-direction. Lastly, the mass of each solar array is taken to be 83.75 kg, as can be retrieved from [2].

2.2.1 Assumptions

- g is taken to be 9.81 m/s
- The center of mass of the solar array is taken to be at the center of pressure of the solar array.

2.2.2 Calculations

In order to calculate the forces in the X and Z-directions, the mass of the solar array is multiplied by the launch load in that direction. Therefore, the forces in the X and Z directions are given by Equations 2.1 and 2.2 respectively:

$$F_x = 2g \cdot 83.75 = 1643.175\ N \tag{2.1}$$

$$F_z = 6g \cdot 83.75 = 4929.525\ N \tag{2.2}$$

Bear in mind that, when analysing a lug that is perpendicular to this one, the magnitude of the force F_y will be the same as the magnitude of the force F_x (since the spacecraft has four solar arrays in two directions). Moreover, to compute the moments caused in the X- and Z-direction, the distance between the center of mass of the solar array and the lug is used as the moment arm d. Since an accurate value was not obtained for what the thickness of the solar panel structure is, an approximation of 3.4cm was used as a thickness of the solar array structure [3], and since on each side of the spacecraft there are solar arrays that are fold-able three times, the center of gravity of the solar panels lies approximately 6cm from the start of the solar panel structure. Therefore a value of 6 cm can be assumed for d. This gives the following results:

$$M_x = d \cdot F_z = 295.8\ Nm \qquad M_z = d \cdot F_x = 98.6\ Nm$$

For the moment in the Y-axis the distance of 1.5 m between the center of mass of the solar array and the lug is used as the moment arm, therefore:

$$M_y = 1.5 \cdot F_x = 2464.8\ Nm$$

2.3 ADCS loads

During the mission, the connection will also have to be able to withstand loads caused by rotating the spacecraft. The ADCS can provide a high angular velocity around all axes. However, to do so, a force and moment have to be carried through and by the connection. The connection should be strong enough to be able to do this. In the free body diagrams shown in Figure 3.1, the forces experienced by the connection are given.

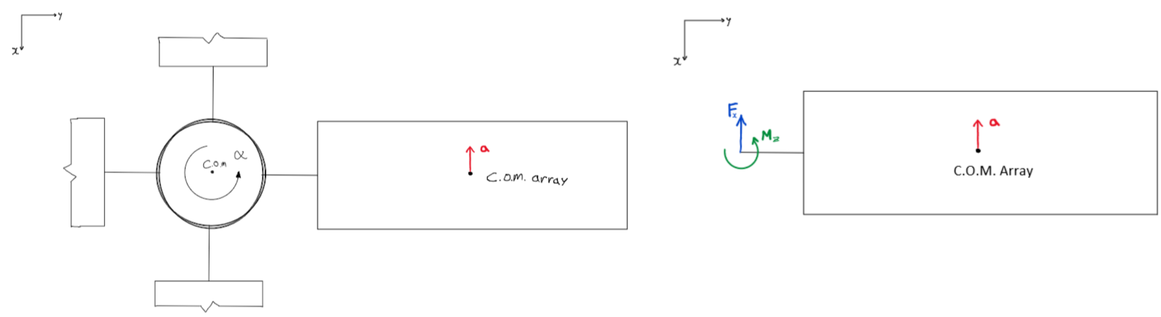


Figure 2.3: Free body diagram of the spacecraft and one array during an ADCS manoeuvre

From [4] it was determined that the ADCS can provide a maximum torque of 120 Nm around each axis. Next to this the moment of inertia around the axis are $I_{xx} = I_{yy} = 11084.22$ and $I_{zz} = 11487.7$ kg·m^2. Using Equation 2.3.

$$\alpha = \frac{\tau}{I} \tag{2.3}$$

The angular acceleration around the axis are found to be $\alpha_x = \alpha_y = 0.011$ rad/s and $\alpha_z = 0.010$ rad/s

With the angular acceleration of the spacecraft the forces through the attachment can be computed using Equations 2.4, 2.5 and 2.6 from [5]

$$\sum F_n = m \cdot \omega^2 r \tag{2.4}$$
$$\sum F_t = m\alpha r \tag{2.5}$$
$$\sum M_G = I_G \alpha \tag{2.6}$$

In order to do so, it is required to know what the mass of one solar array is, which is 83.75 kg. Also the center of mass is assumed to lie in the middle of the array. Therefore, the distance between the connection and the center of mass is $r = 5.8\ m$ [2]. Finally, the moment of inertia of the solar array around each axis is required. Using standard solutions, the mass moment of inertia around the axis from Figure 2.1, are found to be $I_{xx} = 566.8$, $I_{yy} = 49.3$ and $I_{zz} = 616.1$ kg·m^2. With the parallel axes theorem, the mass moment of inertia's around the center of the spacecraft are found to be $I_{Gx} = 3200.8$, $I_{Gy} = 49.3$ and $I_{Gz} = 3250.1$ kg·m^2.

In the free body diagram a positive angular acceleration around Z-axis is considered, however the ADCS is capable of the producing an angular acceleration around all axes and in both directions. So, only the maximum magnitudes of the forces for each axis are important. Due to symmetry, the maximum forces only have to be found for one connection. The axes are represented as in Figure 2.1 and the magnitudes of the reaction moments and forces are provided in Table 2.1.

Table 2.1: Maximum reaction forces and moments in the connection due to a ADCS manoeuvre

Axis	**Force [N]**	**Moment [Nm]**
X	5.3	34.7
Y	$485.75 \cdot \omega^2$	0.5
Z	7.0	29.0

The forces found for maximum angular acceleration are very small, with respect to the forces experienced at launch and thus, do not play any role in designing the connection. However, the force experienced by the connection in the Y-direction depends on the angular velocity and may not be negligible. But, as long as the force is smaller than the force experience during the launch loads, it does not have to be taken into account while designing the connection. The force experienced in the Y-direction during launch is $1643.175\ N$, so the angular rotation may not exceed 1.9 rad/s. Such high rotation rates are very unlikely during the JUICE mission, therefore the launch loads be used for the design.

2.4 Summary of all loads

All the forces and moments acting on the lug are summarized in Table 2.2

Table 2.2: Forces and moments acting on the lug

Load type	F_x **[N]**	F_y **[N]**	F_z **[N]**	M_x **[Nm]**	M_y **[Nm]**	M_z **[Nm]**
Launch Loads	1643.2	1643.2	4929.5	295.8	2464.8	98.6
ADCS Loads	5.3	$454.14 \cdot \omega^2$	7.0	34.7	0.5	29.0

3 Design

In this chapter, the method to determine the design of the attachment is provided. First a configuration and design of the lugs and a fastener pattern on the back plate are provided in Sections 3.1, 3.2 and 3.3 respectively. Those are then iterated on in section 3.4 and the selected final geometry yielding from section 3.5. At last, a material trade off is presented in section 3.6.

3.1 Lug Configuration

The orientation of the solar arrays plays an important role in their proper functioning. The solar arrays will be attached to the vehicle side wall of the spacecraft. Furthermore, the attachments will involve fittings that connect the system to the vehicle and fasteners. An off the shelf attachment configuration is one that involves lugs, this type will be the very basis of the connection.

The configuration of the lug(s) is of paramount importance, as it will influence the distributed loads and therefore the design of the solar array's attachment. Therefore, when choosing a configuration, a solid argument is needed. The design team determined that the double lug configuration is an appropriate option, since it will benefit some aspects of the design. As it mainly is obvious that a double lug configuration will halve the loads acting on one, compared to the single lug configuration. And therefore permit a more weight-efficient design.

To attach the systems to the lugs, various options are possible. However, since the loading includes some bending moments, one double lug configuration connected to the system with a pin, will not be able to carry a bending moment. Moreover, it is not possible to rotate the solar arrays, when placing two lug configurations on top of each other, while it would account for the bending moment by a force couple. Therefore, another attachment should be chosen to counter the bending moment, while also making sure that the solar array is able to rotate. Hence, it is decided that a single lug configuration is placed halfway down on the vehicle side wall, which will still be able to rotate, but also strengthen the resistance against bending.

The attachment is connected in such a way that it will be stronger during launch and somewhat less stronger when deploying the solar array. This is realised by a roll connection on the vehicle wall, which "clicks" itself in a fastened point, when it is fully deployed or fully folded. To elaborate, this is how the roller support will function:

1. The attachment is mounted halfway down of the vehicle wall and has two single lug connections to the solar array. Namely, one oblique connection to the lowest part (end of solar array) and one in a straight connection halfway of the folded solar array.
2. During launch all these connections remain in place and help carry the bending moment that the double lug configuration can not carry itself.
3. During the deployment of the solar arrays, the straight connection will detach from the attachment.
4. Furthermore, since the folded solar array will now extend, the oblique connection is put into roller mode, until the arrays are fully extended and the roller "clicks" into its final position, one quarter down of the vehicle wall.

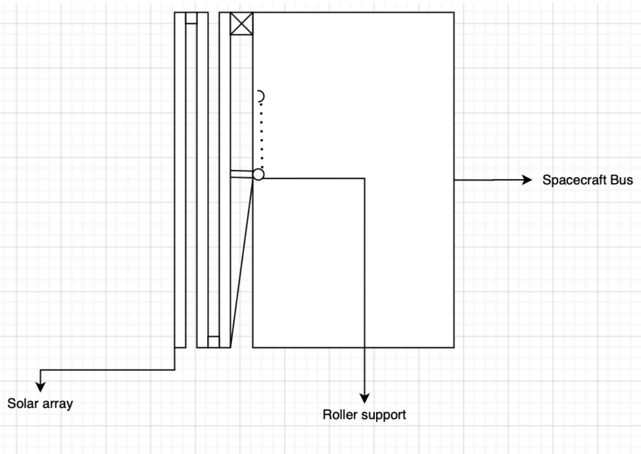


Figure 3.1: Folded solar array

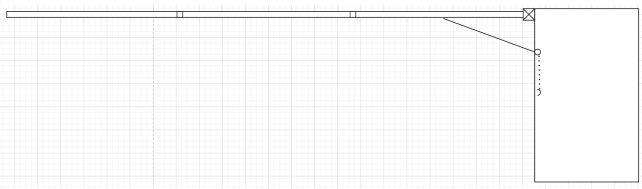


Figure 3.2: Unfolded solar array

Now that the solar arrays are supported in such a way that it is able to account for the bending moment, it is important to find the actual bending moment. Given that the moment in the X-direction will give rise to the force couple F_1, Equation 3.1 can be used to determine F_1:

$$M_z = 2 \cdot h \cdot F_1 \tag{3.1}$$

To find the force couple F_1, one needs to determine the spacing h between lugs in each double lug configuration. The spacing between the lugs is assumed to be 50 mm, since the force couple moment needs to be kept as small as possible. The value of h in the previous designs was considered to be 140 mm, but as this would a too high couple moment, it was decided to use 50 mm. Moreover, the M_z in chapter 2 is calculated to be 95.6 Nm. So re-ordering the equation and filling in gives the force couple F_1:

$$F_1 = \frac{M_z}{2 \cdot h} = \frac{95.6}{2 \cdot 0.05} = 956\ N \tag{3.2}$$

3.2 Design of the Lugs

To be able to design the lug, it is important to compute the force in the Y-Z plane as shown in Figure 2.1 and this could be computed by using the Pythagoras rule, by determining the angle θ between Y and the force P.

$$P = \sqrt{F_z^2 + F_y^2} = 5196.2\ N \qquad \cos\theta = \frac{F_y}{P} = 0.3162$$

$$\theta = \arccos 0.3162 = 71.57\ deg$$

The following equations were used in order to calculate the minimum area requirement.[6]

$$\frac{P}{2} sin(\theta) = K_{bry} F_{tu} A_{br} = 2648.45\ N \tag{3.3}$$

$$\frac{P}{2} cos(\theta) = K_t F_{tu} A_t = 821.38\ N \tag{3.4}$$

Given that the design procedure cannot proceed without a material choice (since the area required depends on properties of the material), the candidate materials chosen for the design is 2024-T3 aluminium and Ti-6Al-4V (Grade 5) , however, in this section the design procedure will be presented with aluminium 2024-T3 as the material choice and will be susceptible to change based on the final trade off. Aluminium 2024-T3 has a tensile yield stress of 345 MPa and a bearing yield strength of 524 MPa.

Now it is possible to use 3.3 and 3.4 and replacing the Areas A_{br} and A_t into functions of D, W and t

$$\frac{P}{2} sin(\theta) = K_{bry} F_{tu} D_1 t \tag{3.5}$$

$$\frac{P}{2} cos(\theta) = K_t F_{tu} (W_1 - D_1) t \tag{3.6}$$

Given that the load in tension is much less than the load caused by shear-bearing load, the lug will be designed for shear-bearing failure. This would mean that the ratio of W/D would be free, since that determines the area at which tension occurs. Additionally, the smaller the ratio of W/D the larger the thickness becomes, this will be explained in the following paragraphs. As we are designing for shear bearing strength its important to take into account all the variables that affect the shear-bearing stress, which would include the different sectional areas around the radius 3.3.

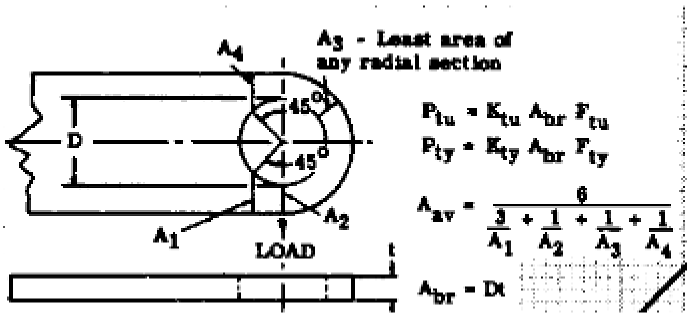


Figure 3.3: Sectional Areas

As shown by the figure 3.3 the ratio $\frac{A_{av}}{A_{br}}$ is important to define the value of K_{ty} that will be used in the analysis of shear-bearing failure. It is represented in the figure 3.3 that A_{av} and A_{br} are calculated using the given formulas:

$$A_{av} = \frac{6}{\frac{3}{A_1} + \frac{1}{A_2} + \frac{1}{A_3} + \frac{1}{A_4}} \qquad A_{br} = D_1 t$$

The areas A_1, A_2, A_3, A_4 could be calculated using the following formulas[7]:

$$A_2 = 0.5(W - D_1)t \qquad A_1 = A_4 = A_2 + 0.5D_1 t(1 - \frac{1}{\sqrt{2}}) \qquad A_3 = a$$

In Figure 3.2 "a" represents the smallest cross sectional area, which in this case is a free variable that we can change based on our design. However, for simplification of the design "a" is taken to be equal to A_2. In order to attain values for the sectional areas, a value for the ratio of W/D should be chosen, therefore it was decided that a ratio of 1.5 would be reasonable, to have a thickness that is reasonable in size. Therefore, the sectional areas become as follows:

$$A_2 = A_3 = \frac{D_1 t}{4} \qquad A_1 = A_4 = \frac{3 - \sqrt{2}}{4} Dt \qquad \frac{A_{av}}{A_b r} = \frac{6}{\frac{12}{3-\sqrt{2}} + \frac{4}{3-\sqrt{2}} + 8} = 0.3317$$

Now, the ratio of $\frac{A_{av}}{A_b r}$ is used to get a value of approximately 0.33 for K_{br} [6]. When the attained value for K_{br} is inserted in equation Equation 3.3, the area A_{br} is $1.53 \cdot 10^{-5} m^2$, and after an applied safety factor of 1.5, the area A_{br} becomes $2.3 \cdot 10^{-5} m^2$. As an initial design, the W required from the following section is 3.12 cm, this would cause the dimensions of D_1 and t to be 2.08 cm and 1.1 mm respectively. Additionally, the lug has to be designed for bending stress due to the forces that are acting on the lug.

$$\sigma_b = \frac{F_x y_1 Y}{I_y} + \frac{F_y}{A} \tag{3.7}$$

$$345 \cdot 10^6 t^2 - 6200.75t - 2455.5 = 0 \tag{3.8}$$

From Equation 3.2 a thickness t_1 of 4 mm has been computed with a margin of safety of 1.5.

3.3 Fastener Pattern Back-Up Plate

The back-up plate of the lug configuration should be connected to the vehicle side wall of the spacecraft. To do this, it has been chosen to use fasteners. However, the number of fasteners to be used and their spacing is crucial in the design process and should therefore be considered elaborately. The designs that will be made here will be used as starting point for the iterations.

There are several design options, the fastener center-to-center distance and two edge distances e_1 and e_2. Furthermore, the spacing between the fasteners D_2 is dependant on the material and the diameter of the fastener. As was found in the previous section, the best material for the lug configuration was the Aluminium alloy 2024-T3. It has been decided to use the same material for the back-up plate.

Additionally, the type of fasteners need to be decided on. The common vented screw is mostly used in spacecrafts, however the team chooses the blind screw as fastener, since these types of screws are better at preventing volatile gasses to leak out or virtual leaks. [8] Now that the material and type of fastener are known, only the diameter of the screw hole for the fastener lasts. When researching the literature for screw holes in fastener plates of spacecrafts, one finds that they mainly are between 0.19-0.25 inches, which is 4.8-6.4 millimeters. Therefore, it is chosen to use 4.8 millimeters as diameter for the screw holes, D_2.

Moreover, the amount of fasteners on one side of the lug design, can be calculated using Equations 3.9 and 3.10:

$$w_{min} = 4D_2 + (k-1) \cdot 2.5 \cdot D_2 \tag{3.9}$$

$$k = \frac{(w - 4D_2)}{(2.5 \cdot D_2)} + 1 = 2 \tag{3.10}$$

Rewriting the equation and filling it in, will give two fasteners for the back-up plate on each side. Therefore the back-up plate will have a total of four fastener holes.

To design the fastener pattern, several design options come into play. These involves the diameter of the fastener, the spacing between the centers of the fasteners and the edge distance. As starting point, we will assume that the diameter of the fastener will be 4.8 mm, based on the Lockheed Martin design for the Juno spacecraft [9].

Furthermore, it is known that the spacing between the centers of the fasteners should be 2-3 times the diameter of the fastener. Thereby, the edge distance should be 1.5 times the diameter of the fastener. For now, the choice of what the spacing between the fasteners should be remains. Specifically, it can be varied between 2 times the diameter and 3 times the diameter of the fastener. Therefore, three different designs can me made, that could be iterated in a next design phase. The design

The width of the back-up plate follows from the following equation:

$$w = h + 2t + 2D_2 + 4e_2 \tag{3.11}$$

h is already defined, namely h=14 mm, we will assume t=1 mm, and as previously said D_2 is assumed to be 4.8 mm and therefore e_2 equals 7.2 mm. The thickness of 1 mm can be assumed since this part will guide as starting point for the iteration.

The height of the back-up plate follows from the following equation:

$$h = N \cdot D_2 + (N-1) \cdot (s - D_2) + 2e_2 \tag{3.12}$$

with N being the number of fasteners which equals 2, s the spacing between the centers of the fasteners, D_2 the diameter of the fasteners, i.e. 4.8 mm, and e_2 the edge distance which equals 7.2 mm.

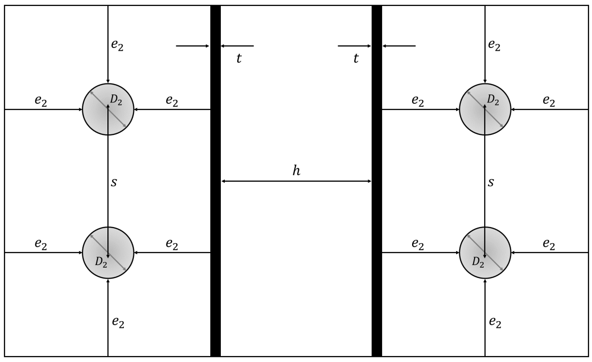


Figure 3.4: Geometry of back-up plate

In figure 3.4 can be seen how the different aspects of the back-up plate relate to its dimensions.

Design 1: 2 fasteners, distance between centers of the fasteners is 2 times the diameter of the fastener: For this design, the width will be 54.4 mm and the height will be 28.8 mm.

Design 2: 2 fasteners, the distance between centers of the fastener is 2.5 times the diameter of the fastener: For this design, the width will be 54.4 mm and the height will be 30.4 mm.

Design 3: 2 fasteners, distance between centers of the fastener is 3 times the diameter of the fastener: For this design, the width will be 54.4 mm and the height will be 32.8 mm.

Putting all this data in a table gives:

Table 3.1: Possible designs

Design	N	s	Width [mm]	Length [mm]
1	2	$2 \cdot D_2$	54.5	28.8
2	2	$2.5 \cdot D_2$	54.5	30.4
3	2	$3 \cdot D_2$	54.5	32.8

Where N is the number of fasteners, s is the distance between the centers of the fastener and D_2 is the diameter of the fastener. With this data, the three different designs can be iterated in further design steps.

3.4 Stress Check

This section, a procedure to check whether the design presented earlier is able to sustain the loads determined in chapter 2 is given. In case it is found that the attachment would fail, the design is altered and the procedure is performed again. This is repeated until an weight-effective concept that can sustain the loads is found. The procedure presented below was coded in Python as given in Appendix A. First, the bearing stress in the fasteners is checked in subsection 3.4.1, then the push/pull through failure mode check are presented in subsection 3.4.2. This is followed by the thermal loads analysis from subsection 3.4.3, at last, subsection 3.4.4 presents the programming in Python of the complete procedure.

The inputs required for the following analysis all come from chapter 2 and consist in the magnitude of the loads acting on the attachment as well as where they are applied.

3.4.1 Fastener Bearing

The bearing stress for the fasteners in the back-up plate is determined in this section. This is done through a number of steps, the first one being to determine the centroid of the fasteners in the plate in the reference coordinate system presented in chapter 2. This is done using Equations 3.13 and 3.14.

$$x_{cg} = \frac{\sum A_i x_i}{\sum A_i} \quad (3.13) \qquad z_{cg} = \frac{\sum A_i z_i}{\sum A_i} \quad (3.14)$$

Here, A is the area of the ith fastener hole. Then, the in plane forces in the X-Z plane must be determined. This is done using the knowledge of the loads from chapter 2, giving information about F_x, F_z, their position (a, b). Then, $F_{cgx} = F_x$, $F_{cgz} = F_z$ the moment around the Y-axis induced by those forces can be computed using Equation 3.15.

$$M_{cgy} = b \cdot F_x - a \cdot F_z + M_y \quad (3.15)$$

With all this information, the in-plane forces can be computed using Equations 3.16, 3.17 and 3.18.

$$F_{ip-x} = \frac{F_{cgx}}{n_f} \quad (3.16) \qquad F_{ip-z} = \frac{F_{cgz}}{n_f} \quad (3.17) \qquad F_{ip-M_y} = \frac{M_y A_i r_i}{\sum A_i r_i^2} \quad (3.18)$$

Where n_f is the number of fasteners, note that F_{ip-M_y} is different for each fastener. The X- and Z-components of the F_{ip-M_y} can be added to the F_{ip-x} and F_{ip-z} respectively, in order to find the resultant in plane load acting on each fastener. The magnitude of the resultant force is then labelled P. The bearing stress is then found using Equation 3.19.

$$\sigma_{br} = \frac{P_i}{D_2 \cdot t_2} \quad (3.19)$$

This can be used to check for maximum bearing stress of the material of the fasteners. The same calculation can be done for the sheet of the spacecraft using its thickness t_1.

3.4.2 Pull/Push-Through Failure

Besides the bearing failure, the lug can fail by pull-through or push-through. The forces that can cause push through or pull-through are F_y, M_x and M_z. F_y is already obtained in section 2. The centroid of the fasteners was calculated in section 3.4.1. So, if the resultant force is acting at a coordinate (x,y,z) of (a,b,c) relative from the center of gravity then M_{cgx} and M_{cgz} will be given by Equations 3.20 and 3.21 respectively.

$$M_{cgx} = b \cdot F_z - c \cdot F_y + M_x \quad (3.20) \qquad M_{cgz} = a \cdot F_y - b \cdot F_x + M_z \quad (3.21)$$

From the reader the following equations are given for the out of plane force per fastener. Equation 3.22 gives the pullout force due to F_y and Equations 3.23 and 3.24 give the pullout forces due to M_x and M_z.

$$F_{pi} = \frac{F_y}{n_f} \quad (3.22) \qquad F_{pM_x} = \frac{M_x A_i r_i}{\sum A_i r_i^2} \quad (3.23) \qquad F_{pM_z} = \frac{M_z A_i r_i}{\sum A_i r_i^2} \quad (3.24)$$

These forces can be calculated with given information of the placing and cross-sectional areas of the fasteners. Afterwards, it should be noted that if M_z is positive, there will be tension to the left of the z-axis in the X- and Z-plane and there will be compression on the right side. So, if a fastener is positioned on the right side of the z-axis, the pullout force due to M_z is $-F_{pM_z}$. Also, if M_x is positive there will be tension under the X-axis and compression above the X-axis. This means that the pullout force due to M_x is $-F_{pM_x}$, if the fastener is positioned above the X-axis.

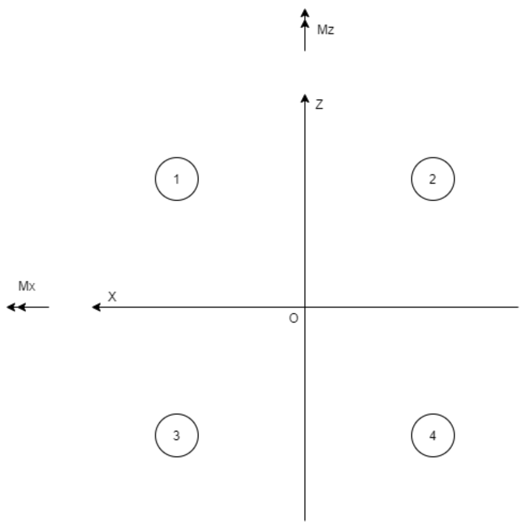


Figure 3.5: Four fasteners positioned around their center of gravity with moments causing pull-through

Now, the total pullout force F_{yi} on each fastener can be calculated by:

$$F_{yi} = F_{pi} + F_{pM_x} + F_{pM_z} \tag{3.25}$$

With these pull/push-through loads known, the stress on each fastener can be calculated. As can be noted in figure 3.6, a positive pullout force on the backup wall will cause the bolt to experience tension and it is deflected up in the positive Y-direction (see Fig. 3.6). This causes the nut under the spacecraft wall to push back onto the spacecraft wall. A negative pullout force (so a positive push-through force) will cause the backup wall to push onto the spacecraft wall, so the bolt will experience no loads. So push-through will not cause failure in the bolts.

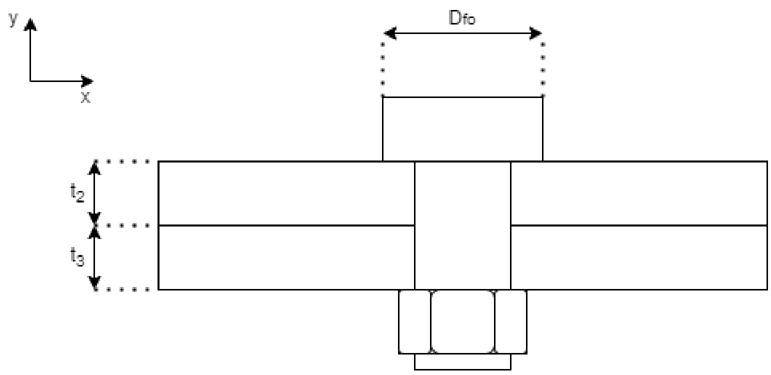


Figure 3.6: Simplified view of a bolt attaching the lug backup wall to the spacecraft wall

The pullout force will cause a shear stress in the backup wall and in the spacecraft wall. This shear stress can be determined from Equation 3.26:

$$\tau_i = \frac{F_{yi}}{A_{shear_i}} \tag{3.26}$$

Here $i = 2$ for the backup wall and $i = 3$ for the spacecraft wall. In Equation 3.26, F_{yi} is the same for both the backup wall and the spacecraft wall. The pullout of the bolt will cause shear around the edge of the head of the bolt along the whole thickness of the plate. So the shear area A_{shear_i} is defined as follows:

$$A_{shear_i} = \pi D t_i \tag{3.27}$$

Again in Equation 3.27, $i = 2$ for the backup wall and $i = 3$ for the spacecraft wall. For simplicity it is assumed that the nut has the same diameter as the head of the bolt. So in Equation 3.27, $D = D_{fo}$ for both the shear stress in the spacecraft wall and the shear stress in the backup wall. So the stresses in both walls are computed using Equation 3.28.

$$\tau_i = \frac{F_{yi}}{\pi D_{fo} t_i} \tag{3.28}$$

In the Python program Equation 3.28 is used for both walls for every fastener. Now, the stresses in both walls are known at every fastener, it will be checked if these shear stresses are below the shear yield stresses of the considered materials.

3.4.3 Thermal loads

The values of the thermally induced force are calculated using the temperatures calculated in previous reports. This can be performed with Equation 3.29.

$$F_T = (\alpha_c - \alpha_b)\Delta T E_b A_b (1 - \Phi) \tag{3.29}$$

Where the α are the thermal expansion coefficients of the bolt and component or wall respectively, ΔT is the temperature difference between the assembly and the the calculated case. A_b is the area of the bolt and Φ is the force ratio. All of these values, except the force ratio, are given by the specification of the bolt, wall and environment. The force ratio however is a bit more involved, it is given by the ratio of compliances of the attached parts and the fastener as follows in Equation 3.30.

$$\Phi = \frac{\delta_a}{\delta_a + \delta_b} \tag{3.30}$$

The compliance of the attached parts δ_a and the bolt are given by Equations 3.31 and 3.32.

$$\delta_a = \frac{4t}{E_a \pi (D_{f0}^2 - D_{fi}^2)} \tag{3.31}$$

$$\delta_b = \frac{1}{E_b} \cdot \left[\frac{L_{h,sub}}{A_{nom}} + \frac{L_{eng,sub}}{A_3} + \left(\frac{L_{sha,1}}{A_{sha,1}} + \frac{L_{sha,2}}{A_{sha,2}} + ... + \frac{L_{sha,i}}{A_{sha,i}} \right) \right] + \frac{L_{n,sub}}{E_n \cdot A_{nom}} \tag{3.32}$$

The compliance of the fastener is calculated as the sum of the compliances of each component of the bolt, such as the head, shank and nut. For the purpose of quicker iterations most of the dimensions of the bolt, such as the head diameter are programmatically estimated from the diameter. For this, the ISO 4762 standard for bolts was analyzed to find average ratios between the major diameter of the bolt and the various other sizes, such as the head height, diameter, the minor diameter [10]. For this purpose a 1 mm thread pitch was assumed, as this thread size is used across many different bolt sizes in the region which the expected fasteners will be.

These equations were implemented in a Python program that is based on the input bolt pattern and sizes calculates the thermally induced forces between each fastener and the wall or the component. This can then be used to assess the bearing stress together with the stress from the loads applied on the bracket.

3.4.4 Iterations

To find the ideal configuration, the python script was extended to try all possible configurations and calculate the margins of safety for the different loading cases. For this purpose, a minimum and maximum for all variables was estimated which would be reasonable for other parts of the design such as the lug. Between these values intermediate values were taken at regular intervals to plug into the margin of safety calculations. All the results were the margin of safety was negative were rejected. For the configurations that did not fail the margin of safety for each fastener in every load case, was added up to a score. This score was then used to rank the different configurations, resulting in the lowest sum of margins of safety possible that is still positive. In total around a million different combinations were evaluated to arrive at the final results. The code used for this section can be seen in Appendix A.

3.5 Final Geometry of the Attachment and Margins of Safety

In this section, the complete geometry of the attachment is provided along with the margin of safety for several parts of the structure using the Aluminium Alloy 2024-T3 for the lug and the fasteners in Ti-6Al-4V (Grade 5). The results were obtained using the Python program from Appendix A that applies the procedure mentioned in section 3.4. The geometrical properties from Figure 3.7 were found as in Table 3.2.

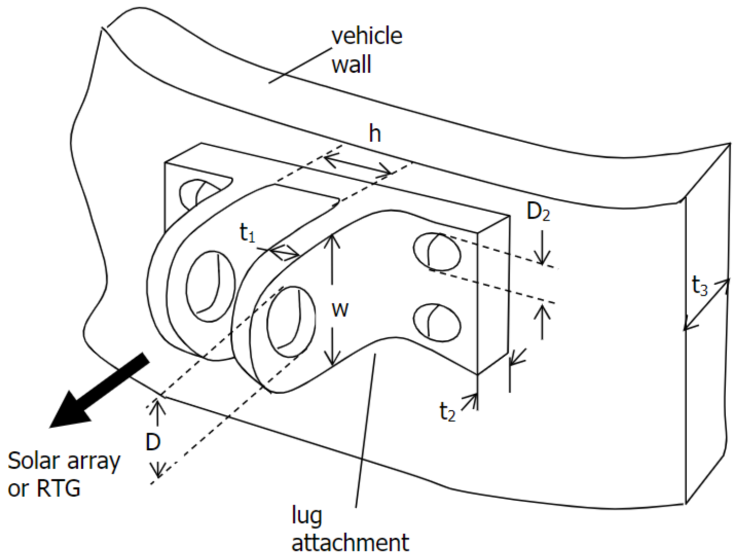


Figure 3.7: Geometry of the attachment (from [1])

Table 3.2: Final geometrical properties of the attachment

Geometry	Value [mm]
w	97.75
D_1	58.78
D_2	8.81
t_1	4
t_2	0.5
t_3	1.35

Note: If the material chosen is Aluminium 2024-T3 The value for w chosen is 97.75 mm, thus for a D_1 of 58.78 mm the ratio W/D has been increased to be 1.663. Therefore the minimum requirement for A_{br} of $1.5359 \cdot 10^{-5}$ using 3.3, and now given that the thickness t_1 of the lug is 4 mm, the shear out-bearing strength would have a margin of safety of 14.36. However, if the material chosen is Ti-6Al-4V (Grade 5) the value of w would be 95.13mm, therefore for a D_1 of 42.28 mm the W/D ratio should be increased from 1.5 to 2.25. Therefore the minimum requirement for A_{br} is $0.3762 \cdot 10^{-5}$ [7]. given that the thickness of the lug t_1 is 2.55mm the Margin of safety of the lug is 27.65. 3.2

The Margin of Safety for each component of the structure is computed using Equation 3.33.

$$MS = \frac{Allowable}{Applied} - 1 \tag{3.33}$$

It is thus seen that if MS is negative in Equation 3.33, then the design is failing in the related failure mode. It is also preferred to keep the MS not too high as this would mean that the problem was over-designed. This was taken into account during the iteration, the margins of safety of the different parts of the structure are presented in Table 3.3.

Table 3.3: Margin of safety for each part of the attachment

Part	MS
Lug	14.36
Back-up wall bearing	20.36
Back-up wall bearing including thermal loads	1.10
Back-up wall pull-through	1.45
Vehicle wall bearing including thermal loads	0.47
Vehicle wall pull-through	0.004

The geometry presented is considered as the most efficient and appropriate for the present mission (using the Aluminium Alloy presented) considering the margins of safety and resistance to the loads. It is now necessary to assess which material is the most appropriate in terms of the cost, mass and load resistance. This is done in section 3.6.

3.6 Material Trade Off

In this section, another lug material (Ti-6Al-4V (Grade 5), annealed) will be investigated for the design (while the fastener material is kept to Ti-6Al-4V (Grade 5) annealed). The complete iteration will be performed a second time with the new material and the result will be compared to what was found previously. This will be done using a trade off as defined below in Table 3.4.

Table 3.4: Trade off criteria

Criteria	Weight	Rationale
Mass	35%	The mass of the lug is important as it will have a direct impact on the complete mass of the spacecraft and thus the cost of the mission. For a fixed mission budget, sparing weight in each part of the structure reduces to alloying more payload to be taken on-board.
Cost	20%	Having a low-cost design is of paramount importance when it comes to determining what the most appropriate design. Having a perfect one that cannot be built because of budget constraints is of course be problematic, therefore, the cost is also considered to assess what material should be use. Note that at this point of the design phase, the cost can hardly be estimated as it is mainly dependent on the manufacturing technique which is not known at this stage yet. Therefore, a qualitative index based on references will be used. This index will range from 1 to 5 (very expensive to inexpensive).
Volume	10%	The volume of the attachment should be kept as small as possible. This makes it easier to integrate it with the rest of the spacecraft while freeing up space for other components such as the payload.
Design goal	35%	The design goal was to minimise the total Margins of Safety while still avoid failure as collapse of the solar panel attachment would result in a direct mission failure. That is the case as no more power would be generated on the spacecraft.

The weight of each criteria was given following the general design strategy. The design goal should be fulfilled as much as possible, therefore it is given the largest weight of all with 35%. Then, the mass has the largest impact on the rest of the mission and is also taken into account with the same weight. The total mission budget being limited, the cost of the structure is taken into account with a weight of 20%. At last, the volume is already known to be small for such system, however it is still taken into account as the total space available on the spacecraft is obviously limited and should be considered carefully. The result of the second possible design using Ti-6Al-4V (Grade 5), annealed is presented in Table 3.5. As the fasteners and the components are made of the same material the thermal forces do not exist. The previously obtained design using Aluminium 2024-T3 was given in Tables 3.3 and 3.2.

Table 3.5: Design using Ti-6Al-4V (Grade 5), annealed

(a) Margins of Safety

Part	**MS**
Lug	27.65
Back-up wall bearing	32.3
Back-up wall bearing including thermal loads	32.3
Back-up wall pull-through	2.85
Vehicle wall bearing including thermal loads	8.53
Vehicle wall pull-through	0.0002

(b) Geometry

Geometry (See Figure 3.7)	**Value [mm]**
w	95.13
D_1	42.28
D_2	2.69
t_1	2.55
t_2	0.5
t_3	1.66

The two designs can now be compared to each other using the trade off presented in Table 3.4. For this purpose, the estimated mass, volume, cost and total MS[1] of each design is given in Table 3.6.

Table 3.6: Characteristics of the designs considered

Characteristic	**Aluminium 2024-T3**	**Ti-6Al-4V (Grade 5), annealed**
Mass [g]	217.22	350.28
Volume $[cm^3]$	78.42	77.84
Qualitative Cost Index [2]	4	2
Total MS	37.744	103.63

From this information and using the previously presented trade off, the most appropriate design can be chosen. As only two designs are being compared, a score of one is awarded to the winner of each section, while the other is simply given a zero. In case the values obtained are sensibly the same, both designs get a half mark. The different scores are given in Table 3.7.

Table 3.7: Scores of the Trade Off

Criteria	**Aluminium 2024-T3**	**Ti-6Al-4V (Grade 5), annealed**
Mass (35%)	1	0
Volume (10%)	0.5	0.5
Cost (20%)	1	0
Design Goal (35%)	1	0
Total Weighted Score	0.95	0.05

From the results of the trade off, it is clearly seen that for the generated designs of both material, the one in Aluminium is much more appropriate. The final design is presented in further details in section 3.7. It is noted that it could have been expected that the design using Titanium would turn out to be better, however the trade off showed otherwise. This stresses the fact that the material properties do not fully determine the quality of a design.

[1]Computed using $MS_{total} = \Sigma(MS_i)$

[2]Based on the discussion from [11]

3.7 Final Design

In this section, the final selected design is presented and a CATIA model of it is provided.

From the material trade off it is determined that aluminium is the better choice and the respective geometrical final design can be found in Table 3.8.

Table 3.8: Final Selected Design (see Figure 3.7)

Characteristics (See Figure 3.7)	**Value**
w	97.75 mm
D_1	58.78 mm
D_2	8.81 mm
t_1	4 mm
t_2	0.5 mm
t_3	1.35 mm
Material	Aluminium 2024-T3
Mass	217.22 g
Qualitative Cost Index	4
Total MS	34.844

With this data a CATIA model could be made. The model of the lug can be seen in Figure 3.8

Figure 3.8: CATIA render of the lug

A technical drawing of the part is also made. This can be found in Appendix C.

3.7.1 Integration of the parts

Now the parts have to be integrated into the design. They are positioned right at the top rim of the spacecraft bus in order to be able to fold in the solar arrays optimally (Fig. 3.9).

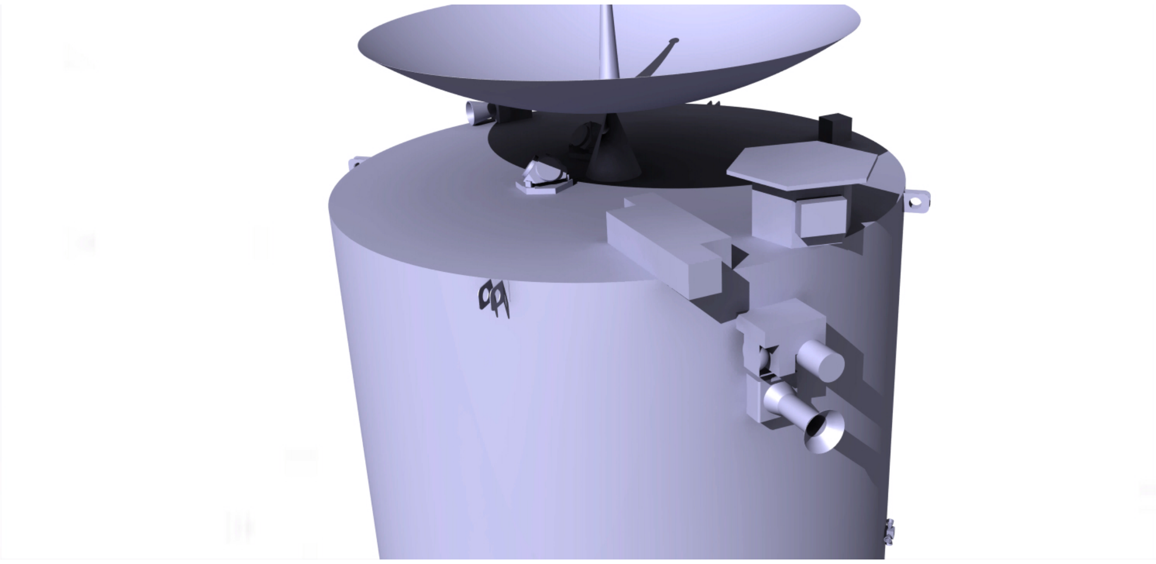


Figure 3.9: Positioning of the lugs

This finalizes the connection between the solar arrays and the vehicle body. The updated spacecraft architecture can be found in Figure 3.10

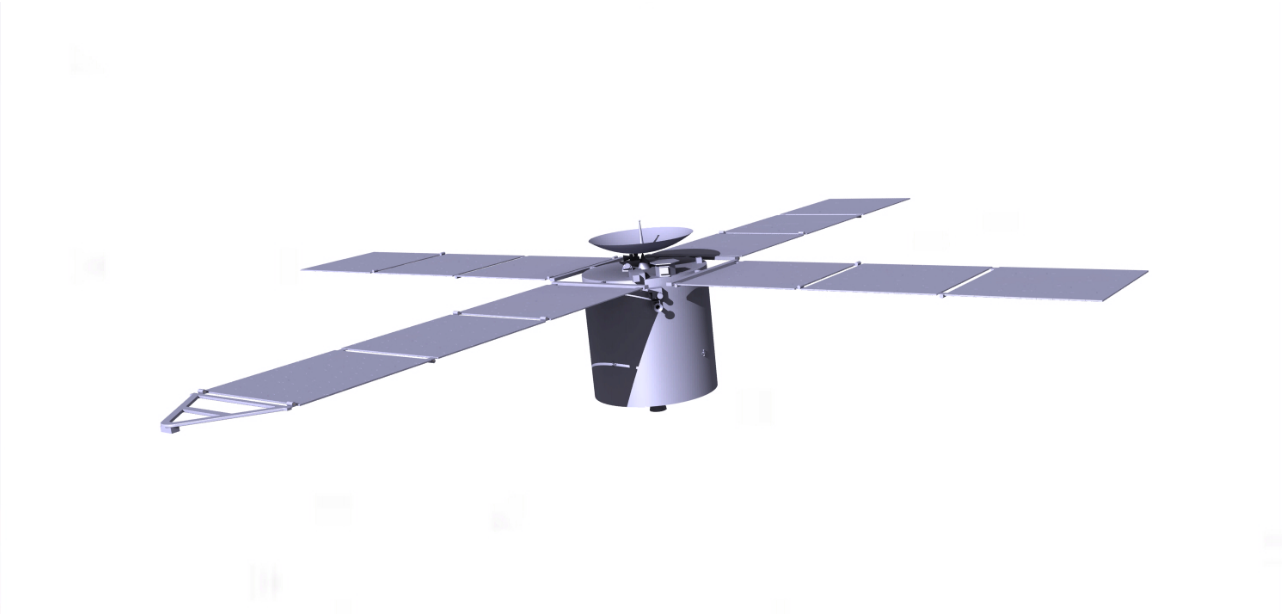


Figure 3.10: Updated spacecraft architecture

4 Conclusion

The aim of this report is to design a lug that is capable of supporting the solar array system, by withstanding the loads that are applied to it. This was done in different steps. First in order to identify which loads the lug should be designed for, two different types of loads were identified, these loads are the Launch loads and ADCS loads. According to the calculations the launch loads were the most dominant. Therefore, the lug was designed for these loads. Then different configurations of the lug were considered, however after some analysis it was concluded that a lug with a double lug configuration seemed to be the most advantageous. An initial design of the lug was then preformed by using different sectional areas of the lug and different failure methods (loads in tension and oblique loads). Finally, based on the initial design, a python code was made in order to iterate different designs of the lug and identify the most appropriate lug design.

The code that was created takes into account many factors. First, the maximum bearing stress of the fastener material is identified by calculating the center of gravity of the fasteners and computing the resultant force to calculate the required stress. Then the fastener plate is designed for pull/push-Through failure which is what occurs when the fastener is pulled/pushed through the fastener plate. Finally thermal loads are then accounted for when the fastener is made of a different material than the fastener back up plate.

Taking into account all the previous steps, the code is used to iterate an optimum design for the lugs, which gives a final geometry of the lug attachment and its margins of safety. However, since different materials have been used to create different final geometries, a material trade off was made in order to decide which material is most optimum for the design. As a result, Titanium Ti-6Al-4V (Grade 5) has been chosen as the material to be used for the fastener, whilst Aluminium 2024-T3 has been used for the lug and the fastener back up plate. The final geometries and the margins of safety are listen below in 4.1.

Table 4.1: Final Design

(a) Margins of Safety

Part	**MS**
Lug	14.36
Back-up wall bearing	20.36
Back-up wall bearing including thermal loads	1.10
Back-up wall pull-through	1.45
Vehicle wall bearing including thermal loads	0.47
Vehicle wall pull-through	0.004

(b) Geometry (See Figure 3.7)

Geometry (See Figure 3.7)	**Value [mm]**
w	97.75
D_1	58.78
D_2	8.81
t_1	4
t_2	0.5
t_3	1.35

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Python Code A

This appendix presents the python code used in chapter 3. First, the functions used are presented and then the main code is shown.

```python
import math


def positionVector(cgPosition, location):
    '''Get position vector
        @INPUT: cgPosition = (cgPositionx, cgPositionz) and location = (locationx, locationz, ...)'''
    locationx = location[0]
    locationz = location[1]
    cgPositionx = cgPosition[0]
    cgPositionz = cgPosition[1]
    return (locationx-cgPositionx, locationz-cgPositionz)


def cg(FastenerCharacteristics): #Works
    '''Find the center of gravity of all the fasteners combined:
        @INPUT: list of the location of each fastener and
                the respective area--> (locationx, locationz, diameter)
        @OUTPUT the location of the center of gravity'''
    sumA, sumForx_cg, sumForz_cg = 0, 0, 0
    for component in FastenerCharacteristics:
        A = (component[2]**2)*math.pi/4
        x_coord = component[0]
        z_coord = component[1]
        sumForx_cg += A*x_coord
        sumForz_cg += A*z_coord
        sumA += A
    x_cg = sumForx_cg/sumA
    z_cg = sumForz_cg/sumA
    return (x_cg, z_cg)


def Force_in_plane(FastenerCharacteristics, cgPosition, Forces):
    '''Find the F-in-plane-x, F-in-plane-z, F-in-plane-My from Fcgx, Fcgz and M_y
        @INPUT: Fx and Fz and their position in an array [posx,posy, posz, Fx,Fy, Fz]
                and should respect sign convention in axes system,
                the characteristics of each fasteners (locationx, locationz, diameter)
        @OUTPUT: F-in-plane-x, F-in-plane-z, F-in-plane-My from Fcgx, Fcgz and M_y'''
    F_in_plane_x = Forces[3]/len(FastenerCharacteristics)
    F_in_plane_z = Forces[5]/len(FastenerCharacteristics)

    rF = positionVector(cgPosition, [Forces[0], Forces[2]])
    #print(rF)
    #print(f"rF = {rF}m")
    My = rF[1]*Forces[3] - rF[0]*Forces[5]
    #print(f"My = {My}Nm")

    #Equation in magnitude
    numerator = []
    mySum =0
    for component in FastenerCharacteristics:
        r = positionVector(cgPosition, component)
        r_total = math.sqrt(r[0]**2 + r[1]**2)
```

```
        A = (component[2]**2)*math.pi/4
        num = My*A*r_total
        numerator.append(num)
        mySum += A*r_total**2
    denominator = mySum
    #print(numerator)

    i = 0
    totalPerFastener = []
    while i < len(FastenerCharacteristics):
        F_in_plane_My = numerator[i]/denominator
        theta = math.atan2(r[0], r[1])
        componentsF_My = (math.cos(theta)*F_in_plane_My, math.sin(theta)*F_in_plane_My)
        F_in_plane = [F_in_plane_x + componentsF_My[0], F_in_plane_z + componentsF_My[1]]
        totalPerFastener.append(F_in_plane)
        i += 1

    return totalPerFastener


def Force_out_plane(FastenerCharacteristics, cgposition, Forces, Mx, Mz):
    '''Forces: [posx, posy, posz, Fx, Fy, Fz]'''

    M_x = Forces[1] * Forces[5] - (Forces[2] - cgposition[1]) * Forces[4] + Mx
    M_z = (Forces[0] - cgposition[0]) * Forces[4] - Forces[1] * Forces[3] + Mz

    F_pi = Forces[4] / len(FastenerCharacteristics)
    Fpulllstz = []
    Fpulllstx = []
    s_ar2 = 0
    # First the sum of Ar^2 must be calculated
    for i in range(len(FastenerCharacteristics)):
        relpos = positionVector(cgposition, FastenerCharacteristics[i])
        r2 = relpos[0] ** 2 + relpos[1] ** 2
        d = FastenerCharacteristics[i][2]
        s_ar2 += ((1 / 4) * math.pi * d ** 2) * r2
    # List of the forces due to Mx and Mz on each fastener
    for i in range(len(FastenerCharacteristics)):
        relpos = positionVector(cgposition, FastenerCharacteristics[i])
        r = math.sqrt(relpos[0] ** 2 + relpos[1] ** 2)
        d = FastenerCharacteristics[i][2]
        a = (1 / 4) * math.pi * d ** 2
        Fpullz = (M_z * a * r) / s_ar2
        Fpulllstz.append(Fpullz)
        Fpullx = (M_x * a * r) / s_ar2
        Fpulllstx.append(Fpullx)
    Ftotlst = []
    # If M_z is positive there will be tension in the part left of the cg (x>0) and compression in the part right of the cg (x<0).
    # If M_x is positive there will be tension in the part under cg (z<0) and compression in the part above the cg (z>0).
    for i in range(len(FastenerCharacteristics)):
        relpos = positionVector(cg(FastenerCharacteristics), FastenerCharacteristics[i])
        if relpos[0] < 0:
            Fpulllstz[i] = -Fpulllstz[i]

        if relpos[1] > 0:
            Fpulllstx[i] = -Fpulllstx[i]

    # Now the total pull out force on each fastener is the sum of Fpullx, Fpullz and Fpi
    for i in range(len(FastenerCharacteristics)):
        Ftot = F_pi + Fpulllstz[i] + Fpulllstx[i]
        Ftotlst.append(Ftot)
    # A list of resultant forces on every fastener is given: [Ftot1, Ftot2, ..., Ftotn]
    return Ftotlst

```

```

def pull_through_shear(force, t, d):
    Area = (d * 2) * math.pi * t
    return force/Area

# calculates thermal load between fastener and both plates
def thermal_f(E_fastener, E_plate, alpha_b, alpha_plate, diameter, t_plate, dT, pitch):

    bolt = bolt_size(diameter, pitch, sum(t_plate))
    therm_forces = []
    for x in range(2):
        compa = compliance_a(t_plate[x], E_plate[x], diameter)
        fratio = compa/(compa + compliance_b(E_fastener, bolt))
        f = Therm_force(alpha_plate[x], alpha_b, dT, E_fastener, bolt[4], fratio)
        therm_forces.append(f)

    return therm_forces


def compliance_b(E_fastener, bolt):
    return (bolt[1]/bolt[5] + bolt[2] / bolt[4] + bolt[0]/bolt[6])/E_fastener + bolt[3]/(
    E_fastener * bolt[6])


def compliance_a(t, E_plate, Diameter):
    return 4*t/(E_plate * math.pi * ((Diameter * math.sqrt(3.5)) ** 2 - Diameter ** 2))


def forceratio(delta_a, delta_b):
    return delta_a/(delta_a + delta_b)


def Therm_force(alpha_c, alpha_fastener, dT, E_bolt, A, fratio):
    return (alpha_c - alpha_fastener) * dT * E_bolt * A * (1-fratio)


def bearingStress(Force, t, d):
    return abs(Force/(math.sqrt(4 * d / math.pi)*t))


def bolt_size(diameter, pitch, L_shank):
    L_head = 0.5 * diameter
    L_eng = 0.4 * diameter
    L_nut = 0.4 * diameter
    d3 = diameter - 1.22687 * pitch
    A_major = math.pi / 4 * diameter**2
    A_minor = math.pi / 4 * d3 **2
    A_head = math.pi / 4 * (diameter * math.sqrt(3.5))**2
    return [L_shank, L_head, L_eng, L_nut, A_minor, A_head, A_major]
```

Listing A.1: Functions used for the iterations

In the following, the code in which the functions are used to perform the iteration is presented.

```
from Functions import *

#materials:
E_titanium = 113.8e9
E_aluminium = 73.1e9
E_isocarbon = 40e9

#bearing strengths
Br_titanium = 1480e6
Br_aluminium = 524e6
Br_isocarbon = 250e6

#shear strengths
```

```
tau_titanium = 550e6
tau_aluminium = 283e6
tau_isocarbon = 43e6

#thermal coefficient
alpha_titanium = 8.6e-6
alpha_aluminium = 23.2e-6
alpha_isocarbon = 4e-5

# INPUTS
#max temperature difference to assembly
dT = -140


#baseline
#xcoord
#zcoord

#fastener diameter
#df = 1.5e-3
#xcoord = 120e-3
#zcoord = 20e-3
# each entry one fastener of form (xcoord, z coord, diameter) [m]
#fasteners = [(xcoord,zcoord,df), (-xcoord,-zcoord,df), (xcoord,-zcoord,df), (-xcoord, zcoord,df), (-1.5 * xcoord, 0 , 2 * df), (1.5 * xcoord, 0 , 2 * df)]
# [posx, posy, posz, fx, fy, fz][m and N]
forces = [0, 50e-3, 0, 1643.2, 1643.2, 4929.5]
moments = [295.8, 2464.8, 98.6]

# thickness of first component and then back wall
#plate_t = [0.0003, 0.0013]



#materials: assigning the properties to the variables with which the computations are done
E_fastener = E_titanium
alpha_fastener = alpha_titanium
E_plate = [E_aluminium, E_isocarbon]
alpha_plate = [alpha_aluminium, alpha_isocarbon]
bearings = [Br_aluminium, Br_isocarbon] # fill out with bearing strengths
shears = [tau_aluminium, tau_isocarbon] # fill out with shear strengths


def main(df = 1.5e-3, xcoord = 120e-3, zcoord = 20e-3, plate_t = [0.0003, 0.0013]):
    fasteners = [(xcoord, zcoord, df), (-xcoord, -zcoord, df), (xcoord, -zcoord, df), (-xcoord, zcoord, df)
                 #,(-1.5 * xcoord, 0, 2 * df), (1.5 * xcoord, 0, 2 * df)
                 ]

    inplanef = Force_in_plane(fasteners, cg(fasteners), forces)
    outplanef = Force_out_plane(fasteners, cg(fasteners), forces, moments[0], moments[2])

    inplaneP = []
    thermals = []
    for x in range(len(fasteners)):
        inplaneP.append(math.sqrt(inplanef[x][0]**2 + inplanef[x][1]**2))
        thermals.append(thermal_f(E_fastener,E_plate, alpha_fastener, alpha_plate, fasteners[x][2], plate_t, dT, 0.0005))

    #print("FORCES[N] for each fastener: \n1. out of plane \n2. Thermal forces \n3. In plane forces")
    #print(outplanef)
    #print(thermals)
    #print(inplaneP)
    #print("\n")
```

```
    #arrays later containing bearing stresses with/without thermal
    bearing_comp = []
    bearing_wall = []
    bearingcompsthermal = []
    bearingwallsthermal = []
    pullComps = []
    pullWalls = []

    for x in range(len(fasteners)):
        bearingComp = bearingStress(inplaneP[x], plate_t[0], fasteners[x][2])
        bearingComptherm = bearingStress(inplaneP[x] + abs(thermals[x][0]), plate_t[0], fasteners[x][2])
        bearingwall = bearingStress(inplaneP[x], plate_t[1], fasteners[x][2])
        bearingwalltherm = bearingStress(inplaneP[x] + abs(thermals[x][1]), plate_t[1], fasteners[x][2])

        if outplanef[x] > 0:

            pullComps.append(pull_through_shear(outplanef[x], plate_t[0], fasteners[x][2]))
            pullWalls.append(pull_through_shear(outplanef[x], plate_t[1], fasteners[x][2]))
        else:
            pullComps.append(0)
            pullWalls.append(0)


        bearing_comp.append(bearingComp)
        bearingcompsthermal.append(bearingComptherm)
        bearingwallsthermal.append(bearingwalltherm)
        bearing_wall.append(bearingwall)


    #print("STRESSES [Pa]: \n1. Bearing (including thermals) of the component \n2. Bearing incl therm wall \n3. Pull thru comp \n4. Pull thru wall")
    #print(bearingcompsthermal)
    #print(bearingwallsthermal)
    #print(pullComps)
    #print(pullWalls)
    #print("\n")


    bearingwallms = []
    bearingwallthermms = []
    pullWallsms = []
    bearingcompms = []
    bearingcompsthermms = []
    pullCompsms = []

    for x in bearing_wall:
        bearingwallms.append(bearings[1]/x-1)

    for x in bearingwallsthermal:
        bearingwallthermms.append(bearings[1]/x-1)

    for x in pullWalls:
        if x == 0:
            pullWallsms.append(0)
        else:
            pullWallsms.append((shears[1]/x)-1)

    for x in bearing_comp:
        bearingcompms.append(bearings[0]/x-1)

    for x in bearingcompsthermal:
```

```
        bearingcompsthermms.append(bearings[0]/x-1)

    for x in pullComps:
        if x == 0:
            pullCompsms.append(0)
        else:
            pullCompsms.append(shears[0]/x - 1)

    succeed = all(i >= 0 for i in bearingwallthermms) and all(i >= 0 for i in pullWallsms) and \
              all(i >= 0 for i in bearingcompsthermms) and all(i >= 0 for i in pullCompsms)


    #print("bearingwall")
    ##print(bearingwallms)
    #print(bearingwallthermms)
    #print("pull wall")
    #print(pullWallsms)
    #print("bearing comp")
    #print(bearingcompms)
    #print("pull comp")
    ##print(bearingcompsthermms)
    #print(pullCompsms)
    #print(succeed)


    return bearingwallthermms, pullWallsms, bearingcompsthermms, pullCompsms, succeed, bearingwallms, bearingcompms


if __name__ == '__main__':

    steps = 32

    working = []
    ms = []

    for a in range(0, steps):
        for b in range(0, steps):
            for c in range(0, steps):
                for f in range(0, steps):
                    # change these values according to constraints
                    df = 3e-3 + a * 6e-3/steps
                    xcoord = 25e-3 + b * 150e-3/steps
                    zcoord = 5e-3 + c * 70e-3/steps
                    t1 = 5e-4 # + d * 5e-3/steps # fixed component thickness to reduce computations
                    t2 = 1e-4 + f * 10e-3/steps
                    ms1, ms2, ms3, ms4, success, ms5, ms6 = main(df, xcoord, zcoord, [t1, t2])
                    if success:
                        totalms = sum(ms1) + sum(ms2) + sum(ms3) + sum(ms4)
                        specifications = [df, xcoord, zcoord, t1, t2, ms1, ms2, ms3, ms4, totalms, ms5, ms6]
                        working.append(specifications)
                        ms.append(totalms)



    print(len(working))
    bestindex = ms.index(min(ms))
    print(working[bestindex])
```

Listing A.2: Main code used for the iterations

Material Properties B

In this appendix, the properties of the materials used or considered for the design of the attachment are listed. Those values for Aluminium 2043-T3, Ti-6Al-4V (Grade 5) and Carbon Fibre Composite Materials can be found in Table B.1.

Table B.1: Material properties

Property	**Aluminium** [1]	**Titanium**[2]	**Composite**[3]
E-modulus [GPa]	73.1	113.8	41
Shear strength [MPa]	283	550	50
Bearing yield strength [MPa]	524	1480	250
Thermal expansion (at 20) °C [µm/mc^{-1}]	23.2	8.6	4.0
Density $[g/cm^3]$	2.77	4.50	2.00
Cost [$/kg]	2.35	20.85	21.5

In work package 2 [2] a carbon nanotube composite is used. However little about this material is known and the material is applied by spraying layers onto carbon fibre composite sheets [17] which makes finding and using the material properties needed for design not possible. Therefore it is chosen to replace the carbon nanotubes with a carbon fibre composite. This however implies a different wall thickness is required. The new value for the wall thickness of the spacecraft is found to be 17.9 mm.

[1] 2043-T3 [12] [**2024t3\$**]
[2] Ti-6Al-4V (Grade 5), annealed [13][14]
[3] Carbon Fibre Composite Materials (fibres at +/- 45 degree with respect to the loading axis) [15] [16][**com**]

C CATIA Drawings of the Attachment

In this section, the CATIA drawings of the attachment are provided.

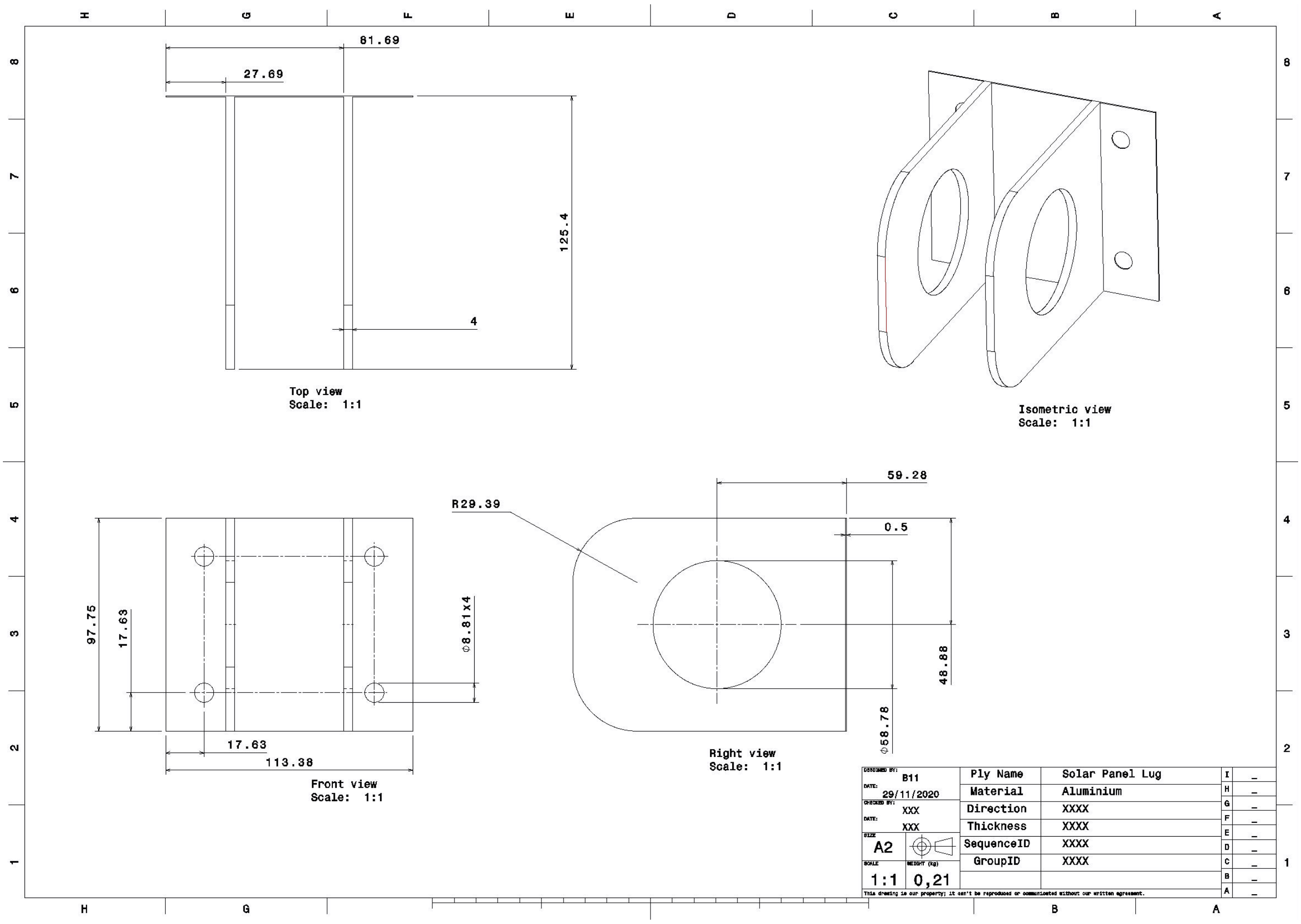

Figure C.1: Technical drawing Solar panel lug

D Task Distribution

Table D.1 presents the task distribution of the various deliverables present in the report.

Table D.1: Task distribution

Task	Made	Proofread
Abstract	Lorenz	Lorenz, Stefano
Summary	Antonio	Lorenz, Jonatan, Stefano
Introduction	Antonio	Lorenz, Jonatan, Stefano
4.1	Antonio, Tarek, Sam	Jonatan, Sam, Stefano, Lorenz
4.2	Silvano, Stefano	Antonio, Jonatan, Silvano, Stefano, Lorenz, Tarek
4.3	Tarek	Antonio, Jonatan, Silvano, Stefano, Lorenz, Tarek
4.4	Silvano, Tarek, Stefano	Stefano, Sam
4.5	Lorenz	Jonatan, Silvano, Stefano
4.6	Lorenz	Jonatan, Silvano, Stefano
4.7	Lorenz	Silvano, Stefano
4.8	Jonatan	Silvano, Stefano, Lorenz
4.9	Niklas, Jonatan	Silvano, Stefano, Lorenz
4.10	Niklas	Stefano, Lorenz
4.11	Niklas	Stefano, Lorenz
4.12	Niklas	Stefano, Lorenz
4.13	Lorenz, Niklas, Jonatan	Stefano
4.14	Lorenz, Niklas	Sam, Stefano
4.15	Jonatan, Sam	Stefano
Conclusion	Tarek	Jonatan, Stefano, Sam
Appendix A	Nilkas, Lorenz, Jonatan	Lorenz
Appendix B	Sam, Lorenz	Lorenz, Sam
Appendix C	Sam, Jonatan	Sam