The flight of a rocket is a complicated thing consisting of multiple stages. But as the saying goes: "What goes up must come down". In order to not endanger anyone on the ground from things that are coming down there is a necessity for a device that is going to slow down and safely land them. For many years there has been a solution that is cost and space efficient - parachutes. In recent years there have been technologies developed for a thrust landing devices, namely *SpaceX Falcon 9*, but these technologies are too complicated and expensive to develop, thus we have naturally chosen to use parachutes.

Air resistance

In order to slow down the falling objects it is necessary to dissipate their kinetic energy in a controlled way. This can be done through the displacement of air and generation of force opposite of that applied to displace the air, in simpler terms: Air resistance. For arbitrary objects there is an empirical equation that describes the air resistance of them. The formula goes as follows:

$$F_D = \frac{\rho v^2 C_D A}{2} \tag{1}$$

F_D - Drag force acting on the object,
ρ - Density of air,
v - Falling speed relative to air,
C_D - Specific drag coefficient (determined experimentally),
A - The effective area displacing the air (for parachutes we use the **full fabric area** in order to simplify calculations).

On this falling object there is yet another constant force acting upon: Gravitational force. For the parachute operating height, it can be assumed that the gravitational force doesn't change, therefore the formula is: $F_G = mg$. When these forces are equal the system is stable and the falling speed is constant, therefore we can express the area for parachute needed to achieve a specific (safe) descent rate.

$$mg = \frac{\rho v^2 C_D A}{2}$$
$$A = \frac{2mg}{\rho v^2 C_D} \tag{2}$$

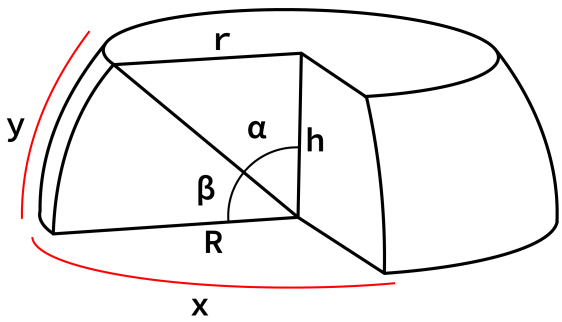
This is the case only if there is no additional air resistance, but in real life there is. If the object specific values $A_{object} \cdot C_{D_{object}}$ for everything except the parachute is known, then the area for parachute's fabric can be calculated with the following equation:

$$A = \frac{\frac{2mg}{\rho v^2} - A_{object} \cdot C_{d_{object}}}{C_{D_{parachute}}} \tag{3}$$

Gore shape

All parachute shapes have their pros and cons. One has a higher coefficient of drag, the other has more stability and so on. The most popular shape of parachute, when viewing professional aerospace engineers at work, is Hemispherical as seen in the picture to the right. This shape is a half sphere, that often has a spill hole. Creating such a parachute is not an easy task, since there isn't a real way to properly lay the spheres surface into a 2D shape. This can be seen in another industry that has been dealing with this problem for a way longer time - cartography. We will not look at cartography though. Reasons to choose this shape are these: It is decently stable with somewhat of a high coefficient of drag (The first parachute we made with this shape had a drag coefficient of 0.62) and, relatively to other more complicated parachute shapes, easier to manufacture. This parachute shape is also pretty hard to tangle.

For parachutes there are some certain requirements that are not just mathematical. For example the parachute gores must be reasonably sized so that a person can manufacture the parachute. The way parachutes are made is no secret - they are made by sewing the gores together. But what determines the exact shape of a gore? The best way to describe the shape is through an equation.



$$\alpha = arccos\left(\frac{h}{R}\right) \quad ; \quad \beta = \frac{\pi}{2} - \alpha = \frac{\pi}{2} - arccos\left(\frac{h}{R}\right) \quad ; \quad r = \sqrt{R^2 - h^2}$$

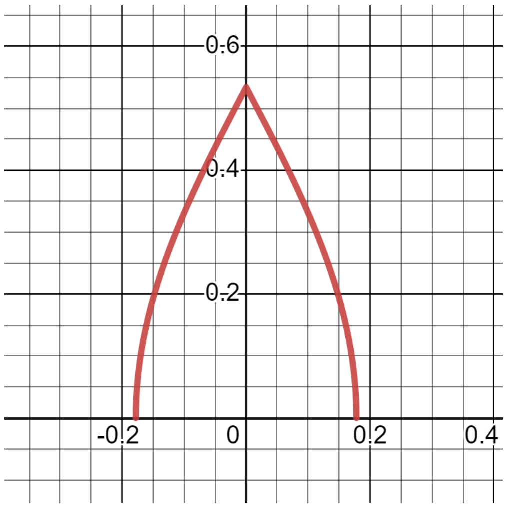
$$y = 2\pi R \cdot \frac{\beta}{2\pi} = R\left(\frac{\pi}{2} - arccos\left(\frac{h}{R}\right)\right)$$

$$x = \frac{2\pi r}{2n} = \frac{\pi r}{n} = \frac{\pi}{n} \cdot \sqrt{r^2 - h^2} \quad \Longrightarrow \quad h = \sqrt{\frac{\pi^2 R^2 - x^2 n^2}{\pi^2}}$$

$$y = R\left(\frac{\pi}{2} - arccos\left(\frac{\sqrt{\frac{\pi^2 R^2 - x^2 n^2}{\pi^2}}}{R}\right)\right) \tag{4}$$

In this equation R is the radius of the sphere and n is the number of gores necessary (**must** be a whole number ≥ 4).

When graphed this equation should look like in the image to the right. It resembles perfectly the shape of a 2D object that is an equal part of a sphere. This is not the gores shape though, because it does not contain the spill hole and the overlaps that the manufacturer will need when sewing. Going forwards from here, we cannot describe our gore only by this equation. Now that we have the general shape we must calculate the height at which we must cut the shape we got from our equation. This cut will give us a spill hole when all gores are assembled. The spill hole should be 3% of the area of half-sphere, thus we must calculate the spheres radius for which the fabrics area will be that of calculations.



The area of a sphere is calculated by the following equation:

$$A_{sphere} = 4\pi R^2 \tag{5}$$

But when we are calculating the areas for our parachute we are dealing with a half-sphere, furthermore only a section of a half-sphere. The area of this section can be calculated using the following equation, where h is the same height as used when deriving equation 4.

$$A = 2\pi Rh \tag{6}$$

We know that the spill hole area should be 3% of the half-sphere, thus we can calculate the h at which the spill hole should start. Since the spill area is 3%, the fabric area should account for the 97% left, so we can write an expression:

$$\frac{2\pi Rh}{2\pi R^2} = 0,97 \quad \Longrightarrow \quad h = 0.97R$$

By using previously established equations we can calculate the exact y coordinate we must cut our gore at.

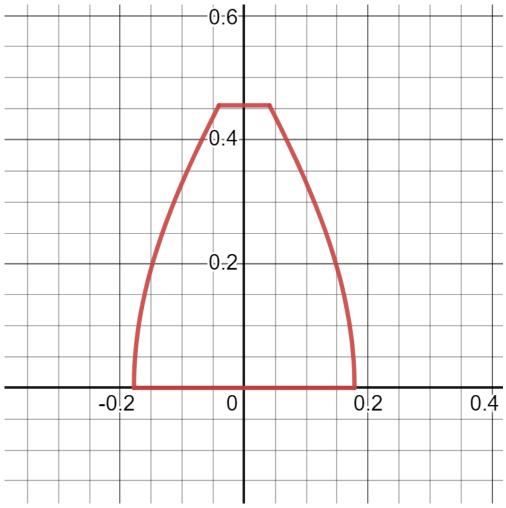
$$A = 2\pi Rh = 2\pi R^2 \cdot 0.97 \quad \Longrightarrow \quad R = \sqrt{\frac{A}{2\pi \cdot 0,97}}$$

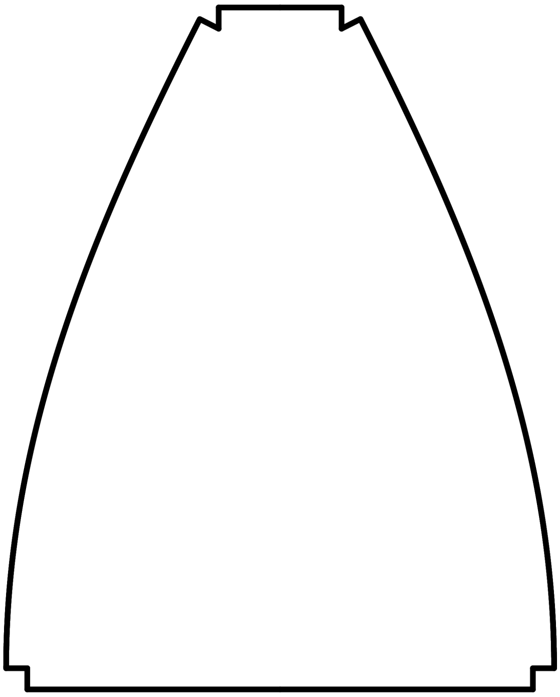
$$y = \sqrt{\frac{2mg}{2\rho v^2 C_D \pi \cdot 0,97}} \left(\frac{\pi}{2} - arccos\,(0,97)\right) \tag{7}$$

Or with the more complicated, but realistic area:

$$y = \sqrt{\frac{\frac{2mg}{\rho v^2} - A_{object} \cdot C_{d_{object}}}{2\pi \cdot 0,97 \cdot C_{D_{parachute}}}} \left(\frac{\pi}{2} - arccos\,(0,97)\right) \tag{8}$$

With all the equations implemented properly we graphically get something as seen on the right. This is way closer to the finished gore shape and only needs slight adjustments. The last part must be done either in a drafting and modeling program such as SolidWorks or in a program that can perform an offset task. The final product must have overhangs on each edge so that the manufacturer can sew the ends off and multiple gores together without sacrificing the detrimental surface area. Depending on the overall mass the parachute is holding, the skills and preferences of manufacturer the overhang may vary. It usually is around 15mm. Note that the corners do not extend outwards like the edges, because when manufacturing it would bring a great deal of trouble. The final product must look like in the image down below.





Luckily for anyone reading this and thinking of making this exact parachute type, there has been a program made that crates a DXF file automatically with the final shape from input data. And if one desires, one can change any constant one likes in these calculations. The program is available online accessible by the following: [LINK]()

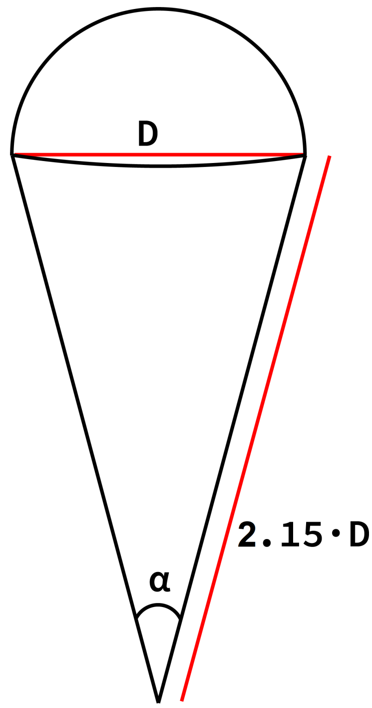
If the link doesn't work please write an email with a request for gore DXF file generator to rtuhprteam@gmail.com.

Manufacturing

Manufacturing process starts when the theoretical one ends. This means that when you start actually doing something you must have all the theoretical part sorted out unless you are experimenting, but experimenting is not advised on high importance projects. The first step in manufacturing is choosing the proper materials to manufacture out of. For the fabric of the parachute we want something that is light, sturdy and wont let air through. So for most applications we chose ripstop nylon or polyester fabric. Depending on the parachute size and intended loads, different thicknesses can be chosen. In rare cases you will want your parachute to be made out of fireproof materials. In any case you shall change the fabrics material, you should be ready for a change in drag coefficient, because different fabrics will perform differently at not letting air through. For the parachute lines we have found that braided polyamide cords work well (in our experience the best). In our previous parachutes we have used the 2mm version, but this thickness value must be enough to withstand necessary loads. Additionally you will need a thread to sew everything together and a braided polyamide sleeve in which you will place all the braided polyamide cords and connect them creating a loop. Fireproof parachutes will need everything made of kevlar.

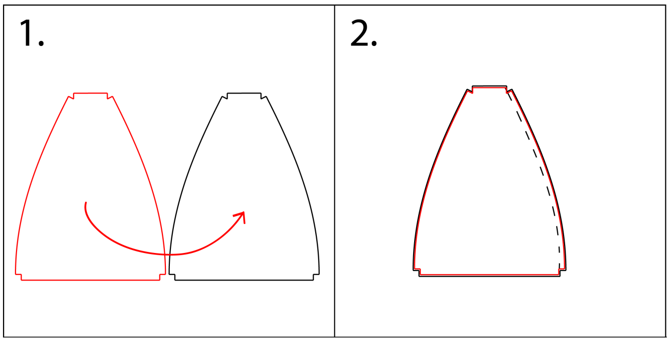
The second step in manufacturing process is cutting out the gores. Multiple methods are available, but better precision leads to superior parachute quality; hence, the laser-cutting method has been selected as the optimal way to cut gores after several trials. The laser cutting method will be extremely precise and fast. Other cutting techniques can be used, but it is not recommended.

A question about the length of parachute lines may arise while preparing them for sewing. When parachute is inflated, the angle between parachute lines should be $\alpha = 25°$-$30°$, so the line length should be about 2.15 times the diameter of inflated parachute (this diameter is just 2 times the radius calculated previously). Don't forget to add the length necessary for connections. It usually is 50cm (20cm at the parachute end and 30cm at the lower end, but these values will change depending on the size of the parachute). An illustrative drawing can be seen on the right side.

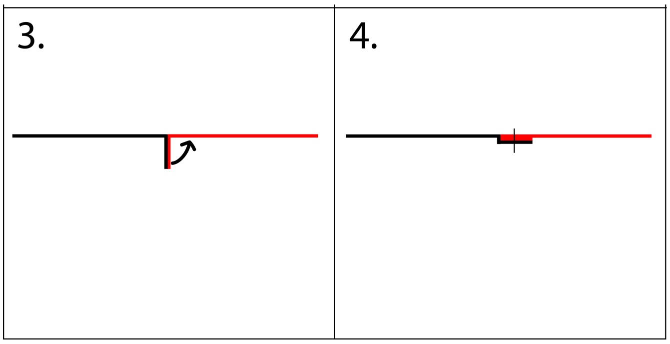


Now comes the most difficult part: sewing. This indeed is quite a challenging task especially if you have no previous experience. Unless you are up for the challenge or you are an experienced sewer, you should outsource this service. In order to do this you will need to create detailed instructions for this task. This is easier said than done, because at different places the sewer will ask different level of detail in the instructions given. So a general solution to this problem will be laid out in this document.

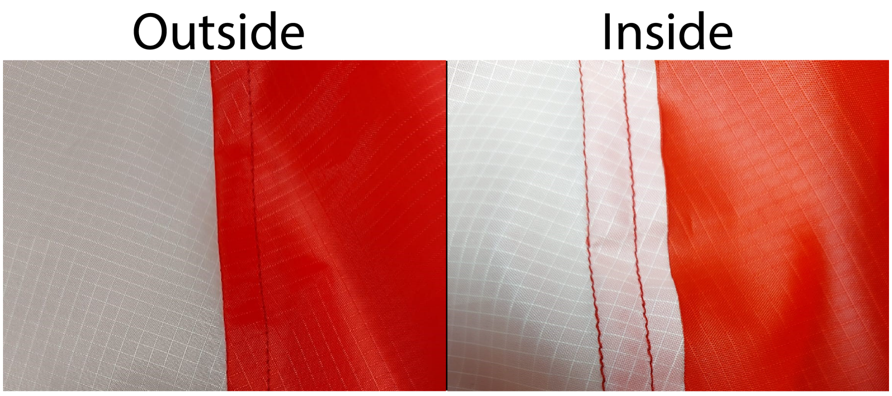
It can be quite a challenge to sew together curved shapes unless you know a little trick. The trick is as follows: two identical gores are laid one on top of each other so that they are perfectly align. If the fabric is not identical on both sides, then the to be outside of parachute sides of fabric on gores should touch. Then one side of the gore is sewed exactly on the stitching line as shown in the illustration.



This process should be repeated until all gores are connected. When this is done, before closing the loop and sewing the last gore with the first, the sewing lines must be straightened. At the places where gores are connected there should be the previously discussed overlaps left. These overlaps are folded to one side (keep it consistent for the whole parachute) and sewed to the main gore section.

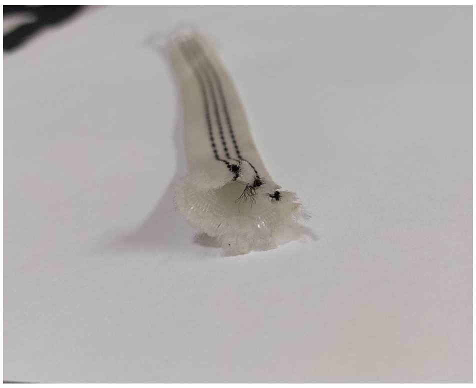


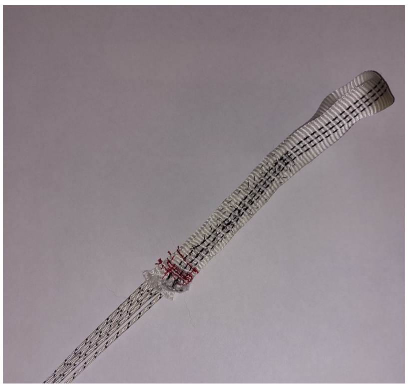
Afterwards in a similar way as shown in step 1 and 2 the loop of gores is closed so that they all are connected in a circular fashion. The 3rd and 4th steps are done to the last connection. A real life example of how the connection should look like is visible in the images below.



Next step is to fold and sew the top overhangs and bottom overhangs to the inside of parachute. This is easily done and a completed example of the upper part overhangs sewed to the inside of parachute can be seen in the image below on the left. When this is done, the fabric part of the parachute is done and when viewed it should resemble the final product. The next step is to attach the parachute lines. You should have about 20cm left for each line you have cut for the parachute attachment and 30cm for the lower connection. The upper attachment is the line folded 10cm from the end and sewed to the top of parachute. The real life example can be seen in the image below on the right.

Last but not least is the lower connection. This connection is very important because all weight goes through this loop and if it is made incorrectly it could fail the loads. To make the connection correctly you will need the braided webbing "tunnel" (seen below on the left), which is cut at a length of 30cm, then pass through it all (the parachute lines untangled) and fix them in place by sewing. Then fold it in half and thoroughly sew about 10cm of the upper end, leaving a nice loop to attach to. The finished end loop connection should look as seen in the image below on the right (note that for fixing lines the red thread was used, but for fixing the loop a lot of white and black thread was used). If the parachute is designed with a lot of these lines, they should be connected individually before the main loop so that the connection point does not get very big.





At this point you should have a fully functional parachute capable of withstanding forces many times greater than its stable flight designed force. The parachute should inflate very well, creating a nice looking half sphere with a spill hole.