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TETHERED INHERENTLY SAFE RE-ENTRY CAPSULE

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ABSTRACT

Young Engineer Satellite YES2 is a project promoted by Delta-Utec and supported by European Space Agency opened to university students all around the World. The aim of YES2 is to build a spacecraft capable to safety land from space onto European soil, so it does not hurt anybody neither the payload breaks. Besides safety, quick and easy recovery after landing are other requirements in mission design.

YES2 project begins when a FOTON satellite reaches the prefixed point in its orbit. After a tether deployment, AIR (**A**n **I**nflatable **R**e-**E**ntry) capsule descends. After a tether extension of 30 Km, and by means of an accurate and precise break in this tether, the capsule, already inflated, would start its descent. Different geometries have been analysed for the re-entry capsule, being the conical and the spherical the most advantageous. Between them, the decision must be chosen taken into account different mission scenario possibilities.

Because of the inherently safety requirement, an appropriate shock absorber must be chosen, in order to land safely somewhere in Europe. But also, it must bear the high temperatures, and to keep its shape in flight.

It is also commented the possible use of a tether as a brake.

1. MISSION ANALYSIS

This project starts with the detachment of the AIR (An Inflatable Re-entry) capsule from the FOTON satellite, which is placed in a low orbit. This satellite is able to place FLOYD, the YES2 part which remains attached to FOTON, and AIR, aligned with Nadir. The tether begins to deploy tether in a first stage, until a pre-scheduled point, where AIR stays in a stable position just below FOTON, aligned in the vertical.

A telecommand from a ground station allows to continue the deployment. After a tether extension of 30 Km, the tether is cut and the capsule, already inflated, would start its descent. From this point until the capsule lands safely and its recovered, several mission scenarios have been evaluated. The most important requirement is the inherent safety of the design. Even when something fails, it must remain harmless.

After the tether is cut, there is no chance for the capsule to remain without entering the atmosphere. So in order to follow the safety condition, the capsule must burn in the re-entry stage if a failure occurs, or land safely.

This condition makes unsuitable for this mission the use of parachutes, or any other device which should be triggered after the re-entry. A failure in any of this devices will provoke the capsule to land in a dangerous and unpredictable way.

Without the possibility of using devices after the re-entry, the chosen capsule design must be unique for all the mission conditions. That is, the same configuration must be able to resist the re-entry, remain stable during the atmospheric trip, and land in a certain area at a very low velocity, and being harmless for people.

So different mission parameters where evaluated in this study:

- Geometry
- Mass reduction
- Shock absorption
- Use the tether as brake.

The objective of this capsule is to accomplish the following requirements:

- The mission is inherently safe. This design is able to land a payload mass without hazard in an inhabited area. A failure in any system will cause the mission to be aborted or the vehicle to burn in the re-entry.
- The landing velocity is below 10 m/s.
- The deceleration in the landing is low. The shock absorption must be able to give appropriate values for the landing while it is also able to absorb the kinetic energy, avoiding damage to people or objects.
- The vehicle could be launched in a volume not bigger than 0.7*0.7*0.7 m^3.

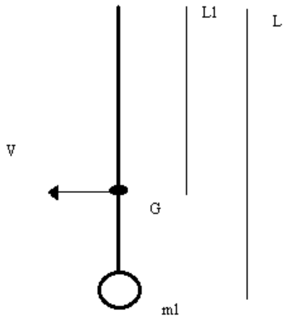
Of course, a device that allows the capsule to be found when it lands must be placed in it. The mission success comes only when the landed payload is recovered, and this can only be done by finding the capsule.

Some devices has been suggested for this purpose, but since this is not the point of this report, only to mention that its weight will be very low, even when a small power supply needs to be carried. The most important thing is the needed protection, as it is payload also, and the screen that several materials, as reticulated carbon foam, can do to the transmission.

2. TETHER ANALYSIS

In order to use the tether as a help for the mission success, its behaviour must be, at least in first approximation, to tail the capsule. If the tether doesn't tail it, the capsule's attitude will not be correct, and it will burn in the re-entry.

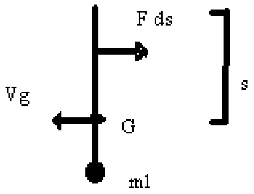
So with the simplifications of taking a rigid tether, placed in the vertical axis, above the capsule, and the capsule-tether mass centre G in circular orbit, it is demonstrated that the momentum is always so that the tether remains tailing the capsule. The following demonstration is based in this picture:



Let be m_1 the capsules mass, 20 Kg approximately for this mission; m_T the tether's mass, 5 Kg for the mission given material for a length L of 30 Km. Calculating the tether length L_1 above G, using a momentum equilibrium in G we obtain:

$$0 = -m_1(L-L_1) + m_T \frac{L_1}{L}\frac{L_1}{2} - m_T \frac{L-L_1}{L}\frac{L-L_1}{2}$$

Calling $\Lambda = \frac{m_T}{m_1}$, we obtain $L_1 = \frac{L}{2}\cdot\frac{2+\Lambda}{1+\Lambda}$



We can calculate the air drag force, assuming that the velocity is the same for all the tether, not depending on s, which is the parameter that measures the distance to G, with a positive value above G. This can be done because the tether length is very small compared to the Earth radius R, and $V(s) = V_G{}^2(1+\frac{2s}{R})$

So, $D = \int_{-(L-L_1)}^{L_1} \frac{1}{2}\rho\cdot C_D\cdot V^2\cdot d\cdot\delta s$, where ρ is the air density and d, the tether's diameter.

The air density is given by atmosphere density model[4] for that region,

$\rho(s) = \rho_G\cdot e^{\frac{h_G-h}{H}} = \rho_G\cdot e^{-\alpha\frac{s}{L}}$, where H=45,91 Km, α=L/H=0,652.

Given as positive turn for the momentum ↺ .

With the known expression for the air drag force, the momentum expression in G can be written.

$$M = \frac{1}{2}\rho_{G_1} C_{D1} V_1^2 S_1 \left(L-L_1\right) -$$

$$-\int_{-(L-L_1)}^{L_1}\frac{1}{2}\rho_G C_D d V_G{}^2 e^{-\alpha\frac{s}{L}} s(1+\frac{2s}{R})\delta s$$

This expression can be simplified by the following approximations, which can be done without loosing the required accuracy: $V_1 = V_G(1-\frac{2(L-L_1)}{R}) \approx V_G$, and $\frac{L}{R} << 1$.

Then, only by substituting the characteristic values of this mission in the equation, we conclude that,

M<0

So the tether can remain attached to the capsule during the early re-entry stages without being a problem for the manoeuvre. And if properly used, it can help to brake the capsule, and to maintain attitude and avoid certain instabilities, but no further conclusions can be obtained with this simple model.

This conclusion allows to use the tether when designing the different mission stages. And this is very positive in two ways: it is helpful for the mission success but also it assures that the tether will be pulled to the atmosphere and burned in the re-entry.

3. GEOMETRY

As an inflatable capsule, many geometries can be used, but after a first trade-off, the conclusion is that the most suitable for this mission are either the conical or the spherical.

The spherical shape is the most suitable for the early re-entry stages. This geometry allows to reduce speed very quickly in the early re-entry stages, when the atmosphere's density is still very low. That allows to maintain the maximum temperature not as high as expected in an ordinary re-entry, if the capsule is light enough.

On the other hand, due to instabilities, it may have to be shielded in all its surface to avoid damage in the re-entry.

Another problem is that, in order to avoid causing any harm to people or objects when landing, a shock absorber may be placed. In an spherical geometry, this is a difficult task. So the design must be shock absorber by itself.

The conical geometry admits a shock absorber in its nose, so this is an important advantage over the spherical geometry. This shock absorber may also have a heat shield task, protecting the payload form the high temperatures of the re-entry. The nose is going to support very high temperatures because of the close shock wave in the supersonic stages.

It can be done in a much more lighter way, which is a very important thing to be taken into account. That’s because inflating o cone shield requires little structure, while being surrounded by a spherical cover need more attachments the inflatable part.

Also, the way of inflating an spherical capsule with the payload inside is a complex task compared with inflating an open conical shape. It will be more difficult to eject mass from a closed geometry.

The conical shape has also some disadvantages: the hottest points are placed in the nose, but also in the upper part of the walls. This has been concluded in this way after CFD simulations done for a cone shaped capsule of similar dimensions and angle. The values may not be characteristic for this capsule, but certain conclusions are also valid for this design

So as for the spherical shape, the heat shield may also need to be extended to the walls, making then a heavier capsule.

After a trade-off between this two options, and different alternatives for each design, a cone-shaped capsule with an spherical rigid nose has been found as the best choice.

4. CAPSULE DESCRIPTION

The mission requirements are quite the same as the characteristics that SPRInT design meets. Students from Delft University of Technology designed this capsule, in 2000. This capsule is an inflatable cone-shaped one.

AIR mission begins when the tether is cut and the re-entry phase starts. At that moment the inflation should be completed.

Once the tether is cut, the capsule will enter the atmosphere with an angle of 1.5º, and a velocity of 8 Km/s. These values are approximate, as the final mission values will be obtained after an iterative process between the design and the requirements.

The capsule will eject a platform, which carries all unnecessary components before entering the atmosphere. That way AIR will be much lighter, being able to land at the desired velocity. If the ejection fails, the capsule will be too heavy, burning in the re-entry.

The inflation will be done with pressured bottles of helium, which will help to reduce the terminal velocity by making it lighter. The vehicle consists of a rigid titanium payload bay, in which besides the payload all the electronics are situated, with underneath it titanium gas cylinder to inflate the vehicle. The remainder of the construction is totally inflatable.

The inflatable part consists of a lower torus and an upper torus, beams connecting the toruses, cloth that creates a mantle around the beams, and internal construction beams that connect the payload bay with the inflatable parts. The nose cone is a non-inflatable part which is able to absorb the maximum heat and also to absorb the shock.

The payload bay is divided in two parts: The lower part contains the items we want to land and the rest, that is, the on-board equipment (gas bottles, batteries, antennas, etc) is contained in the upper part. This last part, which we will call platform, will be ejected from the capsule.

The shape of the platform is circular and has a circular hole in its centre. It is circular to prevent the inflatable structure being damaged and to adapt itself to the form of the cone, and the purpose of the hole is to let the tether pass free through it.

This ejection operation is very risky, and the probability of failure during the operation is high.

Another option is to eject the platform once in the re-entry. The platform may be attached to the tether, and the tether tension in de re-entry will easily pull out the platform away from the capsule.

Both alternatives needs further study, for a definite capsule design, but mass ejection can dramatically improve the capsule's characteristics.

5. MASS EJECTION

To make a landing capsule inherently safe, its landing velocity must be as low as possible. The capsule must be able to survive to the re-entry, but also to land slowly.

The capsule must be as light as possible, so a mass ejection before the re-entry is suggested. Because no more operations are going to be done during or after the re-entry, and the capsule has been already inflated, there is no need of certain equipment. The amount of ejected mass is unknown at this moment, but for further calculations we will do the following assumption over the landed mass. This assumption has been done using available data about other inflatable structures, and estimating, knowing the materials characteristics, the approximate weight using the dimensions of the designed capsule.

The satellite weights 20 Kg, which is an approximate maximum weight allowed for this design. On the other hand the landed mass will be:

- 3 Kg payload, and necessary structure as heat shields, shock absorbers, etc.
- 5-Kg inflatable structure.

Up to 12 Kg can be the amount of ejected mass because the landing weight is assumed to be of 8 Kg maximum. This is a delicate matter because a difference of 12 Kg must be decisive for a correct re-entry. Some ways of assuring that the capsule burns if the mass ejection fails may be:

- Steeper angle of re-entry
- Enough increase of velocity so that drag would burn it.
- Instability. Maybe the mass centre too high so that it turns over or the re-entry without spin may cause the capsule to become statically instable.

All the mass which is going to be ejected should be attached to a flat disc-shaped platform. The bottles which contains the gas to inflate the capsule, are designed to leave a certain percentage of gas inside after the inflation. The gas remaining is expelled and this fact thrusts the platform upward (due to the principle of action-reaction). The positions of the bottles can be used (if we put them in a certain angle) to give the capsule a light spin and so to have more stability. This spin will also give the platform stability in its ascension. In this second phase, the platform rises over the capsule one or two meters.

A few seconds after the ejection, the platform is divided in two parts. We make this division by using a couple of springs activated by a mechanical chronometer or mechanism. The cut line has been previously mechanised on the platform.

After the division, the two remaining parts will be far enough from the capsule to begin the re-entry carrying only the items we want to land. These two parts of the platform will get burned in the atmosphere.

6. SHOCK ABSORPTION

Another key point of the mission is the landing shock absorption. With the cone-shaped design, a shock absorber must be placed in the nose. The nose will not be inflatable due to the mission requirements. For this mission, a rigid nose has several advantages:

- It is possible to cover it with some ceramic material, which has enough resistance to the re-entry conditions so that no refrigeration will be needed.
- By the use of a ceramic, which will be burned in this stage, it will show an

elastic surface made of several protection layers as Nexel, MLI and alumina. This will be enough to sustain the damage of the last re-entry stage if needed.

It is necessary to assure that the ceramic cover will be burned because if it's not, there is hazard of harming when landing. So there must be under the ceramic an appropriate layer to support some seconds in that conditions.

In the nose it will be placed the material which will absorb the impact shock.

6.1 Shock absorber

The shock absorption is a key point for the mission success. Two concepts have been developed, and both of them are fully compatible with what have been exposed until this point.

One of it is based in the use of silicon gels and foam, materials which are capable of dissipating a great amount of energy when the impact occurs. Also, they are very useful as a heatshield for the payload. The weak point of these materials is the low mechanical properties.

The other concept uses Cold Hibernated Elastic Memory (CHEM). Its mechanical properties are quite good and it is able to get an appropriate shape for the last flight stage. This way, the mission gets the characteristics of a two-stage re-entry vehicle.

One shape is given for the re-entry by the ceramic cover, while CHEM gets with the heat a final geometry with better properties for lower velocities.

6.2 Concept 1

Shock will be absorbed by high tenacity material placed in the nose. At a terminal velocity of 10 m/s, a mass of 7 Kg has a kinetic energy value of 350 J. This mass is a rough estimation of the final landing mass, after the platform ejection before or during the re-entry. It takes into account the structure, the payload, and the possible devices that the capsule must carry so it is possible to found it when it lands. The distance from the lower point of the nose to the payload is around 0.3 m. That will cause severe accelerations to the payload. Reducing this acceleration is possible by presenting a rigid outer edge in the nose, which is not possible because of the safety requirement.

So a balance must be found between acceleration supported by the payload and transmitted shock to the landing surface.

Brittle materials are a good choice for this task, but the vibration test is barely passed by few of them.

Reticulated vitreous carbon foam is an open cell material with exceptional chemical inertness, high temperature strength, and low thermal conductivity. By filling the nose with this material it is assured a temperature of about 300 K for the payload. It's brittle.

Failure mode is very localised and predictable. It has been widely tested, both in static and dynamic tests. It is able to survive to 140 db (0-500 Hz) for 1.5 min of acoustic severe launch loads. Increasing temperature from 300 K to 400 K and 525 K reveals only a 20 and 28.6 percent reductions in strength respectively. Depending on further studies it could be tailored to different densities, according to the mission necessities.

This may be covered either by the Nexel, alumina and MLI layers as the whole vehicle it is, or by a stiffness-based composite sandwich.

The payload would be placed above the platform bay. It will be enclosed in an aluminium or titanium box. Its walls will be very thin. The box will be filled with a very reticulated silicone gel. It is required that it has a viscosity over 10^4 cp. This material is not flammable, it is not degradable, and it frees no smoke. It is able to support temperatures of 400 K. The main purpose of this is to absorb some of the impact shock to the payload.

With these two materials, we achieve a balance shock absorber between the ground impact, which is cushioned by the carbon foam, and the payload shock, reduced by the silicon gel. The structure deceleration comes from the crush stroke. It should be designed so that the nose collapses the maximum distance with this purpose.

The payload shock will be transmitted to the platform bay. Its area is much bigger than the payload's recipient. This makes that the carbon foam receives a lower pressure, distributing the shock absorption along all the foam material. The pressure shock concept is used, as a

Because of the structural requirements of the nose in the re-entry it may be needed to give some stiffness by adding a layer with structural properties. It must be able to support the aerodynamic pressure, but to be flexible to allow an elastic impact or to break under a shock (like vitreous materials). It must be studied if a sandwich composite or an alumina layer is able to give the right mechanical properties.

5.3 Concept 2

The cone nose is the most exposed part to high temperatures, therefore it will carry an ablative heat shield, plus several layers of different materials (MLI,..) in order to keep the CHEM temperature below a certain value.

This shield will protect the nose when the highest temperatures are reached, i.e, the first part of the re-entry, hypersonic regime. During this trajectory, the shield will start its sublimation, which also helps refrigeration.

When it is completely sublimated, the CHEM will be directly exposed to the air flux, so that its temperature will increase until it reaches the T_{cr}. At this point, the CHEM will "explode" and the nose will take a spherical shape (similar to a car airbag, but using temperature as a trigger instead of the car crash). This "airbag" will act as a shock absorber during the landing.

The capability of energy absorption of CHEM is temperature dependent. As a high temperature (over its glass transition temperature), it is lower. Therefore, we think it may be feasible, if the temperature is not very high, which is our case. However, further studies will be necessary, especially those concerning CHEM and high temperatures.

Here are some gross numbers:

To obtain the terminal velocity we use:

$m\ g = ½\ \rho\ V^2\ S\ C_D$

where

$S = \Pi\ R^2\ m^2\ (3\text{-}4\ m^2)$

$C_D = 1$

$g = 9.8\ m/s^2$

$\rho = 1.225\ Kg/m^3$

$m = 7\ kg$

$s = 1m$

The CHEM will have to absorb energy until the velocity descends to zero. The amount of energy is:

$\Delta E = ½\ m\ (\ V_T^{\ 2} – 0\ ) = 350\ J$

For the concept 1 shock absorber, the reticulated vitreous carbon foam is capable enough to absorb the impact getting the mission under the requirements. Due to the materials density, a detailed calculation the mass necessary to fill in the nose volume is to be done. The weight increase shouldn't be a handicap for the mission development but it could be a limitation for other satellite's subsystems.

Silicon gel is a very common material family, and it's cost and availability makes worth its use. There is a big variety of this materials and further study is again needed to choose the right one.

To maintain the structural integrity of the nose, alumina could be used. Reference[1] makes this material useful for this purpose, but depending on when the ceramic cover is burned, it could not be good enough.

A composite sandwich structure could solve the structural material. An studied composite, with 0.001 m thick face sheets are 2-D triaxial braid textile of intermediate modulus graphite fibre in a polyamide-class resin. The core is 0.0127 m of 40 Kg/m^3 carbon foam. This material has been widely tested and the results are again very suitable for this task. CFD simulation for aerodynamic pressure on a spherical layer has been done, passing the requirements. The only problem is that calculations must be done to make this composite either fragile or elastic enough to avoid hazard in landing. The inherent safety makes even more important to calculate the landing and the possibility of becoming harmful, than the performance of the capsule, or its resistance to the flight.

For concept 2, as it has been widely explained, CHEM is a suitable material if we take the assumptions about it. It will also avoid many missions problems by its usage. Characteristics and price must be taken into account when choosing one of the shock absorption concepts.

After comparing these two concepts, CHEM can be able to give much better performance that reticulated carbon foam. It is able to make the capsule change its geometry, which is a key point for the mission success, but that it is not possible to do it in any other way due to safety requirements. A change of the geometry will need a device to be triggered as explained before, except if we do it this way.

I the other hand, we have no certain information about this material, and it has not been widely enough tested to be included in a design. Another problem is that a change of geometry needs to be done in a very precise moment, and even then it exist danger for the mission.

A non symmetrical change of the capsule's geometry will produce serious instabilities, that will probably cause the mission to fail. And, even when the change is done in a smooth and uniform way, this change may begin when the capsule is changing its flight regime between supersonic and sonic or transonic ranges. This possibility must also be taken into account, while the geometry change comes from a temperature variation, and this is likely to happen when changing the flight regime. In this cases, the mission will surely fail.

So the reticulated carbon foam has been found as the most suitable option from the ones that have been evaluated. It is easy to acquire and manufacture, and has been widely tested.

7. TETHER AS A BRAKE

In the capsule's atmospheric flight, two factors will be decisive for a safe descent:

- The capability of reducing as much velocity as possible in the upper atmosphere layers.
- An adequate geometry and mass distribution of the capsule to avoid dangerous instabilities.

While heat dissipation is related to v^3 and to air density, it is very important to reduce as much velocity as possible in the upper atmosphere layers, where the air density is still low. That way, we will be able to enter the lower atmosphere layers with a lower velocity, so the overall heat dissipation will be lower. Of course, we must dissipate this heat with enough time, or we will raise the capsule's temperature too much.

In order to accomplish this, it's important to mention that the air drag force can be calculated by:

$$D = \frac{1}{2} \cdot C_d \cdot S \cdot \rho \cdot V^2$$

Where D is the drag force, C_d is the drag coefficient, S the exposed surface to the air flow, and ρ the air density.

The capsule's surface is of 3 or 4 m^2. But a rough estimation of the tether's surface, for a 0.5 or 1 mm diameter cable, shows that its surface is big compared to the capsule. So, if the tether tails the capsule and help in the braking manoeuvre, this can be much more effectively done.

In order to maintain the tether under certain, an inflatable balloon can be placed at the tether's edge. This balloon gives a big drag force, pulling from the cable. This way, we have an extra drag force, and we avoid by placing a balloon the instabilities that the tether can cause to the capsule at those velocities due to tether's oscillations. By giving an extra tension in the edge, the tether will remain more straight and stable.

For YES2 mission, this may not be feasible because the tether is 30 Km long, which means that most of the tether will still be out from the atmosphere when the capsule is in the re-entry stage. So it will be helpless, or even dangerous because tether's mass can be big compared to the capsule's, and if the tether's velocity is too big compared to the capsule's, it can even not tail it, and provoke the mission fail.

But by the use of a small thick tether, maybe deployed just before the re-entry, we can have many advantages in order to accomplish this mission.

The use of the tether as a brake is similar to aerobrake captures, using the tether's drag force, but also the braking force and the attitude control of the balloon that may be placed at the tether's edge. It

8. CONCLUSIONS

Without the possibility of triggering devices after the re-entry stage so the mission remains inherently safe, some mission scenarios are proposed.

Two different geometries have been discussed, showing in this paper the main advantages and disadvantages that made our group choose the cone shaped instead of the spherical shape.

The mass ejection shows to be important with the purpose of maintaining the safety requirement. So it is an essential point when working on the conceptual design for this mission.

Maybe the most critical point for this mission is the possibility of becoming dynamically instable in the different atmospheric flight stages. Spherical geometries have less problems because of their symmetry. Instabilities may make them roll around their centre, but they will not change its trajectory in an important way. The only thing is that maybe all the wall must be protected.

In a cone-shaped capsule, instabilities become more dangerous, since they are only symmetrical around its axis. But the possibility of ejecting mass and of using a tether as a braking device make it advantageous over the spherical option.

Considering all these factors, a cone shaped capsule has been discussed, showing the feasibility of this concept design for accomplishing the task. This capsule is, in many aspects, similar to SPRIntT. Inflated with helium, but with a rigid nose where the shock absorber will be placed, this design may be close to the mission requirements, The main difference is the refrigeration, which now is not as effective as in SPRInT, but the chosen materials may be able to resist also the re-entry conditions.

Anyway, additional braking will be very useful since capsule's requirements will not be so high. The use of a tether with braking purpose is a useful way of braking, since most of the dissipated heat goes to the cable and to the attached balloon, while the capsule remains cooler. There are other problems that can be avoided if this option is taken into account when designing the capsule, as instabilities, and that is even more important for a cone shaped capsule since a non-symmetrical geometry may turn over itself, causing the payload to get damaged, and landing at a non-adequate velocity.

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