Electric
solar
wind
sail

ESAIL D53.1
Failure mode and recovery strategy analysis report

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Applicable documents

AD1 (D52.1) Conceptual E-sail designs and specifications for component development

AD2 (D41.1) Requirements specification of the Remote Unit

AD3 (D41.2) Design description of the Remote Unit

AD4 (D24.1) Auxiliary tether report

AD5 (D46.1) Simplified FEEP design report

AD6 Janhunen, P., A. Quarta and G. Mengali, Electric solar wind sail mass budget model, *Geosci. Instrum. Method. Data Syst.,* in press, 2013

1. Introduction

The purpose of this WP (WP53, “Refined design concepts”) is to further refine the E-sail design concept which was chosen as a baseline earlier in WP52 (“Design concepts”). The purpose of this document, “Failure mode and recovery strategy analysis report”, is to analyse possible failure modes and their recovery strategies of the baseline E-sail concept (E-sail with Remote Units equipped with cold gas or ionic liquid FEEP propulsion and dynamically stabilised by stretched auxiliary tethers, Fig. 1).

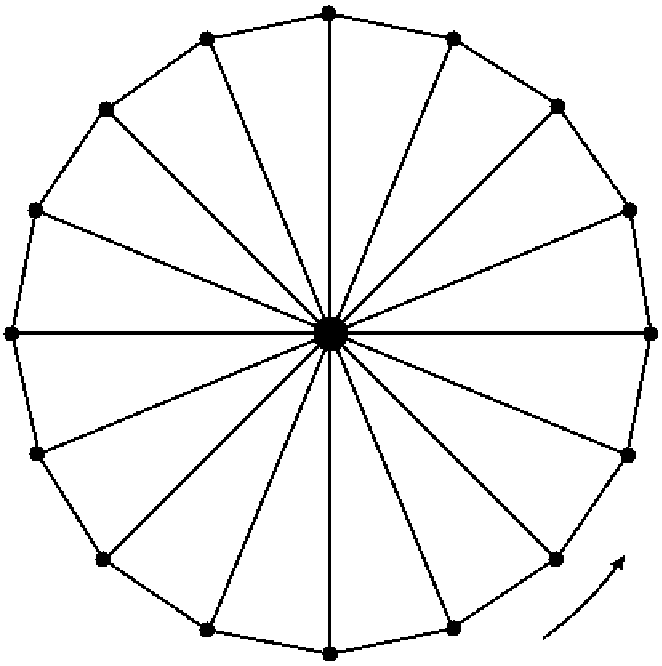

Figure 1: The baseline model E-sail with stretched auxiliary tethers

The scope of this analysis includes the E-sail specific parts of the spacecraft at a generic level: main tethers, Remote Units, auxiliary tethers, electron gun, tether cameras. A complete failure mode and recovery strategy analysis is beyond the scope of the document. Furthermore, our main emphasis is on tether and Remote Unit related risks because they are the ones which are prototyped to more detailed level in the ESAIL project (while for example the electron gun and its high voltage source are not).

2. Failure mechanisms and recovery strategies of E-sail specific parts

We will now discuss each E-sail specific hardware part in turn, identifying its main failure mechanisms and discussing their level of severity and, when applicable, analysing possible recovery strategies.

2.1 Main tethers

The main tethers are the most characteristic and important part of the E-sail. As long as a tether does not break (get cut), it fulfills its function completely. We take it as self-evident that since the tether is made of aluminium, it stays electrically conducting unless mechanically broken, in other words that we do not have to consider a separate failure mode where the tether would fail to conduct while remaining mechanically intact.

The required overall reliability level is mission specific. There are three main strategies to achieve high reliability:

(1) One designs the tethers so that their breakage is very unlikely. Then, if a tether fails, the mission might also be allowed to fail.

(2) One devices a strategy which allows the mission to recover from a tether breakage event. Then, if the recovery strategy can be shown to be reliable, tethers could use a more relaxed design principle because their breaking would not be catastrophic.

(3) A hybrid of (1) and (2).

Our approach is that all three options are still available to us. Our tether design (Heytether [1]) is such that it allows one to scale the reliability of the tether by changing the number of the loop wires. The baseline is to have a 2-3 cm wide 4-wire Heytether (one parallel and 3 loop wires) which according to Grün et al. micrometeoroid flux model [2] gives about 1% failure probability during the first 5 years in 1 AU space for a full-scale 1 N E-sail having a total of 2000 km of tether. The failure probability depends linearly on the total tether length, but its dependence on exposure time is nonlinear. The 4-wire tether appears sufficiently reliably to most applications. For still higher reliability one could add a fourth loop wire. If one does that, one would probably also want to somewhat increase the tether's width, to make an optimal tradeoff between the two main failure mechanisms: small micrometeoroids breaking individual wires randomly and a larger and much rarer gravel-sized meteoroid that could break the whole tether at once.

We also have a procedure by which the E-sail could recover from a main tether breakage event. If a tether breakage is detected, the tether is cut from both the main spacecraft end and the Remote Unit end. The Remote Unit prototype (D41.2) contains a jettisoning device for doing this and the main tether mechanism is currently baselined to use a knife cutter for this purpose. The main concern for the recovery strategy is to guarantee that the broken tether pieces will not collide with other tethers, because if they do, there is a risk that the collided upon tether might also be cut which might yield to a cascading process. The way to avoid collisions between the cut tether pieces and other tethers is to have them in different planes. We propose to do this by giving the main spacecraft a small impulsive delta-v (~2 m/s is enough) by an onboard thruster. This manoeuvre drags the spacecraft and the tether rig attached to it away from the plane where the cut tether pieces are moving radially outward. As a precautionary measure, the voltage is zeroed on all tethers so that there is no potential difference between the cut tether pieces and the rest of the tethers. Thus if despite the delta-v manoeuvre the tethers collide, the collision will not produce a spark which would increase the likelihood of additional tether cuts.

We have not yet settled on the question what is the best way to detect a tether breakage event if it occurs. Among possible sensors are an accelerometer onboard the Remote Unit or a device which senses the presence or non-presence of the high voltage of the tether which is attached to it. Some kind of electromagnetic cable radar type device might also be used, although no quantitative analysis has been made on this. A challenge for the tether breakage detection system is that false alarms are basically not tolerated. We propose that at least two sensors based on different physical principles should signal tether breakage before deciding to invoke the tether cutting and jettisoning procedure.

Thus, our strategy is to have a scalable design for the tethers which allows in principle any reliability level by varying the number of loop wires, and to have a procedure for recovering from tether breakage events.

In addition to micrometeoroids, a tether could break because of too high physical loading tension (caused by unexpectedly violent dynamics of the tether rig, too rapid rotation rate due to miscalculation or malfunctioning tether rig spin control, strong tether oscillations induced by thermal contraction of the tethers due to flying into eclipse or other reason), because of a manufacturing error (e.g. three or more consecutive weak or failed wire bonds with a micrometeoroid cutting the base wire at the same point), due to mechanical fatigue caused by too much oscillations, or by degrading of the aluminium strength because of too high equilibrium temperatures encountered due to closeness of the sun. Our strategy is to avoid risky conditions: our default radial distance range is 0.9-4 au and by default we do not allow flying the E-sail into eclipse. In any case, if a tether breaks for any reason, the recovery procedure is always the same.

If a main tether reel gets stuck during deployment (after that they are not needed any more), either by failure of the motor, bearing or the tether getting physically stuck, one either stops the deployment of all tethers (a viable option if the reel got stuck near the end of the deployment) or one has to jettison the stuck tether using a similar procedure as in case of main tether breakage event.

2.2 Remote Units

The Remote Unit is rather complex and consequently it can fail in many ways, but fortunately in most cases the different Remote Units act as backups of each other.

The Remote Unit thrusters (cold gas, ionic liquid FEEP or photonic blade) are mutually redundant, thus a failure of a single thruster (during deployment or during E-sail flight) is not problematic. A problem can arise only if so many thrusters fail that the total delta-v budget (in case of cold gas or FEEP) or thrust (in case of photonic blade) gets threatened by multiple malfunctions.

The Remote Unit auxtether reels are only needed during tether deployment. Since one Remote Unit contains two auxtether reels and each auxtether is thus reeled from both ends. If an auxtether reel fails, the corresponding auxtether reaches 50-100% of its planned length, depending on if the failure occurs early or late in deployoment. Optionally, if the auxtether reels contain spare capacity, the resulting shortening of the auxtether can be less. If the spare capacity is 100%, there is no shortening even if a single reel fails.

If the whole Remote Unit fails during deployment (e.g., by power or telemetry system failure), both left and right auxtethers remain shorter than normal unless there is spare capacity. If the whole Remote Unit fails and if the same main tether breaks so that it should be jettisoned, jettisoning of the farther part cannot be done if the Remote Unit is unresponsive. In that case, the broken piece of the tether remains attached to the dead Remote Unit. If that piece is long (almost the whole tether), the resulting imbalance to the tether rig might be of fatal level.

According to dynamical simulations, if a single auxtether remains shorter than the others, the E-sail still functions although its dynamical behaviour is somewhat crippled. Depending on the level of ambition of the mission and other factors, the tether rig being unsymmetrical might or might not imply some modest performance limitations.

Even if there is spare capacity on the auxtether reels, a reel failure will make the Remote Unit masses unequal, inducing some dynamical differences to the tether rig.

Our baseline is to not include some spare auxtether capacity.

Specifics of the ionic liquid FEEP version of the Remote Unit

The baseline is to have odd-numbered Remote Units to have an accelerating FEEP and even numbered ones (or vice versa) to have a decelerating FEEP. The odd and even numbered Remote Units are otherwise identical except that the FEEP thruster points in different direction. This is done to enable spin control (both accelerating and decelerating thrust) but to avoid having two FEEP thruster per Remote Unit which would increase their mass. The baseline is to run each FEEP slit alternately in positive ion emitting and negative ion emitting modes without local neutraliser cathode. Then the main tether performs the function of grounding the Remote Unit to the main spacecraft. In order to keep the main spacecraft and the tether rig overall quasineutral, the same number of FEEPs must operate in positive and negative modes at a given moment of time. To keep the chemical composition of the ionic liquid FEEP propellants constant, the positive and negative polarities of the FEEPs must be swapped every now and then (every few minutes, for example).

If a FEEP thruster or a Remote Unit fails, the other thrusters must be run so that overall quasineutrality is maintained at all times. This may mean that another FEEP thruster on another Remote Unit is not run while the others are run nominally. If using FEEP thrusters, it may be necessary to implement a closed loop control where an electron spectrometer onboard main spacecraft (which is for other reasons included in our baseline diagnostic instruments) monitors the spacecraft potential and tunes the voltages of the positive and negative FEEPs accordingly to maintain the spacecraft potential close to zero.

2.3 Auxiliary tethers

The auxiliary tether ring is a single point failure part: if any of the auxtethers breaks, the tether rig collapses due to the centrifugal force pulling the remaining auxtethers outward and thus pulling the main tethers together on one side of the spacecraft. After such event the E-sail does no longer produce thrust, although it might be possible to continue the mission without propulsive capability by cutting all main tethers and thus freeing the main spacecraft from the E-sail completely. Thus the auxtethers must be overdesigned against micrometeoroid damage and mechanical durability by a significant margin.

For completeness we want to mention that in case of auxiliary tether breakage, one might be able to delay the disaster by jettisoning (separating) all tethers from their Remote Units so that the all Remote Units and the damaged auxtether ring get separated from the tethers. The bare tether rig might then work for some time as an E-sail, but it is likely that soon (in hours or days) the tethers would collide with each other one at a time and get tangled, even if one would try to avoid it by somehow carefully modulating the tether voltages. In due course this would then stop the E-sail from producing useful levels of controllable thrust.

Our baseline design for the auxtethers is 3 cm wide 12.6 μm kapton tape which is perforated about 50% to give the tape a suitable spring constant, selected by the criterion of giving the most stable behaviour in dynamical simulation (D24.1). The patterning is done so as to give the tether an U-shaped form when put under tension which increases micrometeoroid tolerance in comparison to a flat tape. The maximum tensile load encountered by the auxtether ring is about 0.6 N in a full-scale 1 N E-sail rig, whereas a non-punched 3 cm wide kapton tape has an ultimate tensile strength of 95 N. We think that our auxtethers are designed such that breakage is very unlikely.

There are also auxtether-free E-sail designs [3,4] based on having enough (photonic) thrust on the Remote Units to enable one to fly them actively and thus avoid mutual collisions.

2.4 Electron gun

The electron gun is a mission critical part. Redundancy must be used if lifetime of the cathode and/or the HV power source is a concern. Fortunately the mass of the electron gun is not very large compared to the total E-sail mass so that the mass penalty resulting from redundancy is not so severe.

2.5 Tether cameras and E-sail control system

In general the control algorithm needs to know the pointing direction of each tether and its corresponding Remote Unit. For this purpose, tether cameras are used which are able to see the Remote Units and possibly also the root parts of the tethers. The Remote Units can be identified by their optical beacon signals.

In principle this information is not completely necessary during flight: eventually it is likely possible to fly the E-sail "blindly", without being able to detect the location of the tethers and their Remote Units. However, at least in the first demonstration mission one wants to verify that the tethers are pointing in the way they should.

The E-sail electronic control system is obviously a mission critical part whose reliability can be achieved by standard means of space electronics design (redundancy, etc.).

3. Discussion and conclusions

Table 1 summarises the main failure modes of the various E-sail subsystems, their level of criticality, possible recovery strategy and the main ways how to prevent failure.

Subsystem	Failure mode	Mission critical	Recovery strategy	Prevention
Main tethers	Breakage	no	Cut and jettison	More subwires
Remote Units	Various	no	Usage adjustments	Safer design
Auxiliary tethers	Breakage	yes	-	Design margin
Electron gun	Malfunction	yes	-	Redundancy
Tether imagers	Malfunction	no	-	Redundancy
Controller	Malfunction	yes	-	Redundancy

Table 1: Main failure modes of E-sail subsystems

Mission critical failures can occur in the auxtethers, the electron gun and the E-sail controller. For the electron gun and the controller these risks can be effectively managed by standard design redundancy without incurring a significant mass penalty. For the auxtethers the risk is in our opinion taken care of by the large design margin that the 3 cm wide U-shaped kapton tape auxtether has against micrometeoroid damage under the maximally 0.6 N pull strength requirement.

The E-sail can at least attempt to recover from a main tether breakage event by jettisoning the broken tether from both ends and by performing an evasive manoeuvre using an impulsive onboard thruster (using ~2 m/s of delta-v). To guarantee that the evasive manoeuvre is able to avoid collisions between the broken tether piece and other tethers would require detailed knowledge how and if the tethers oscillate when in use. While dynamical simulation have provided some light on this question, those simulations do not necessarily contain a fully realistic model especially for the damping properties of the tethers and auxtethers. For this reason a test mission in the real environment is probably needed before a reliable prediction of the success rate of the jettisoning procedure can be made. At the moment our approach is to continue keeping the tether jettisoning procedure in the design (even if its success rate cannot be at this point accurately predicted, although is plausibly above 50%) while having a scalable geometric design for the main tethers which allows one to reduce the risk of tether breakage to a minimum if required. Calculations based on existing models of the micrometeoroid environment predict that already a 4-wire Heytether achieves an acceptably small tether breakage probability (~1% over 5 years), even for full-scale 1 N mission class and without considering tether jettisoning.

Most of the failure modes of the Remote Unit are such that they can occur only during deployment (auxtether reel failure) or they are manifestly taken care of by the natural redundancy of the many Remote Units (thruster failure). If an auxiliary tether reel gets stuck during deployment, the tether rig will be unsymmetrical. According to dynamical simulations, any asymmetries in the tether rig generally cause less dynamically stable E-sail flight. Whether or not such asymmetries would cause performance or manoeuvrability limitations of an E-sail is something which is not easy to predict firmly based only on simulations. For studying that kind of questions it seems that a solar wind test mission would be mandatory.

If a main tether reel gets stuck during deployment, the tether jettisoning procedure must be invoked (unless the incident occurs near the end of the deployment in which case leaving the tethers slightly shorter would also be an option). The success rate of tether jettisoning should be rather high if done during deployment because no solar wind induced oscillations have yet occurred in the tether rig. Nevertheless, jettisoning a tether also causes a permanent asymmetry in the tether rig, similar to a shorter than nominal auxtether or heavier than nominal Remote Unit.

4. References

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[4] Janhunen, P., Electric sail, photonic sail and deorbiting applications of the freely guided photonic blade, *Acta Astronautica,* submitted, 2013.