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Autonomy and Operational Concept for Self-Removal of Spacecraft: Status detection, removal triggering and passivation.

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Abstract

The technology for self-removal of spacecraft, short TeSeR, is an innovative project of 11 partners led by Airbus D.S within the HORIZON2020 framework of the European Union. The main idea is to develop a removal module that can be carried into orbit by future spacecraft of any size and mass into any orbit, interconnected only by a standardized interface. At early 2019, a prototype shall already have demonstrated the main functions. This paper presents the autonomy considerations for the design of the overall post-mission disposal module and focuses on three areas: the status detection of the host S/C by the PMD module, the removal triggering by the PMD module in case of lost link to ground and malfunctioning host S/C as well as the passivation of the host S/C and the PMD module itself.

Keywords: post-mission disposal; autonomous operations; self-removal; passivation; status detection;

Acronyms/Abbreviations

CONOPS	Concept of Operations
LEO	Low Earth orbit
PMD module	Post-mission disposal module
RCU	Removal control unit
S/C	spacecraft
SDU	Status detection unit
TeSeR	Technology for Self-Removal of Spacecraft
TM	telemetry

1. Introduction

As a counter measure to producing more and more space debris, to be included in future Earth orbiting spacecraft of any size, mass and orbit, the Technology for Self-Removal (TeSeR) project proposes a post mission disposal (PMD) module to be carried into orbit by each future spacecraft. Thus, the spacecraft's proper disposal after ending its operational lifetime for whatever reason (nominal end of mission, fuel outage, severe spacecraft failure, mission loss) shall be ensured. In order to do so, the PMD module provides a robust, reliable and highly autonomous operations concept that enables the PMD module to detect the hosting spacecraft's faulty - and supposedly mission ending – status, to secure the spacecraft by passivation and to trigger either a safe de-orbit or re-orbit and final disposal of the spacecraft.

This paper focuses on the PMD module's on-board autonomy, health status detection of the hosting S/C on-board the PMD module, the removal triggering and passivation even in case of lost link to the ground for the novel concept of self-removal.

One basic case and three different cases and levels of autonomy with respective operational approaches including the appropriate removal triggering process are defined within the project. Especially when it comes to mega constellations, the autonomous approach for the self-removal with an attached PMD module is an attractive solution for orbital debris mitigation: the workload of ground operators can potentially be reduced and thus, the overall operational cost go down by using a standardized, series production removal module that takes care of the entire removal process, starting with the detection of the spacecraft's mission ending status.

A list of detectable symptoms is provided that indicate a non-healthy spacecraft. Different types of sensors are investigated with respect to their potential contribution to detect those symptoms of the host spacecraft on-board the PMD module. The sensors are traded systematically considering their additional benefit, weight and power consumption and the best combination of sensors for the status detection purpose is proposed.

A brief investigation of a possible autonomous removal triggering by the PMD module shows that this option is again attractive in case of low cost host S/C.

The passivation of the host S/C is a crucial aspect before its removal and shall prevent its accidental break-up, which would cause even more space debris. The paper informs about relevant space debris mitigation guidelines, gives the definition of passivation and summarizes the most frequent solutions. An analysis about the possible passivation measures for the host S/C from the PMD module without additional hardware and consequences with respect to the successful removal, if passivation fails, concludes the paper.

2. The TeSeR Project

The idea of the TeSeR procet is to explore concepts and develop a removal module that is

- Independent of the host S/C.
- Cost-efficient, possibly by series production.
- Flexible.
- Scalable to S/C of any mass, size and orbit.
- Standardized I/F from PMD module to S/C and to removal subsystem („plug & play“).
- Designed modularly.
- removing either by de-orbiting or re-orbiting.

Finally, the manufacturing and testing of an on-ground prototype will conclude the project.

Funding of over 2.8 Mio. Euro for 11 partners from five different countries is granted by the European Union within the H2020 framework. The project runs from February 2016 until January 2019.

At the Institute of Space Technology and Space Applications of the Bundeswehr University in Munich, the system design of the overall module is done (refer to [1]) including the investigation of beneficial on-board autonomy features like the independent status detection of the host S/C, autonomous removal triggering in case the host S/C is out of control and subsequent passivation of the host and the PMD module itself.

3. Autonomy Considerations

For the design of the PMD module, three different design cases (basic or simple, advanced and prototype) are considered, as can be found within Figure 1.

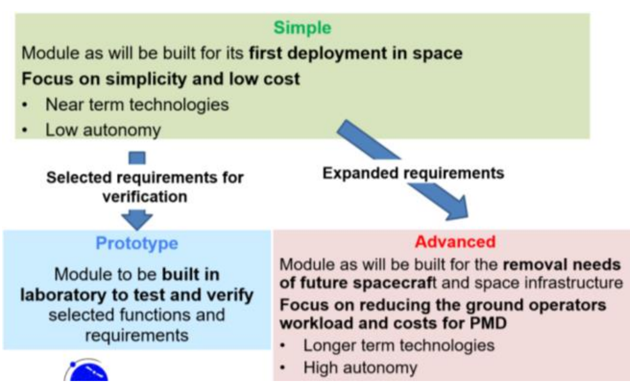

Figure 1: PMD module design cases.

During the proposal phase of the project, the research and application of high autonomous status detection, removal triggering and passivation methods was fancied. But during the early project phase, from discussions with industrial partners and s/c operators, it became obvious that first of all, confidence in the novel approach of self-removal has to be build by using a basic approach that will only remove the s/c from orbit after the host S/C has been successfully decomissioned.

Nevertheless, a long term application, i.e. the advanced PMD module design case was developed in parallel.

For obvious reasons, the removal triggering of a S/C will most likely involve a human operator in the loop for the foreseeable future.

This is surely true if considering costly, highly complex, one-of-a-kind scientific spacecraft. The number of housekeeping parameter of such spacecraft that are to be monitored is easily in the range of 30.000. In this case, an autonomous removal triggering and thus, killing the precious S/C by a third party PMD module is indeed not anticipated.

But on the other hand, the current trend goes towards relatively simple cubesat-sized mega-constellations with several hundreds of S/C simultaneously in orbit. In that case, the operational cost of monitoring and failure recovery of each S/C in orbit will probably exceed the cost of having removed the faulty S/C autonomously and launching a spare S/C for replacement. In this scenario, the application of an advanced PMD module with relieved reliability requirements seems much more likely.

This hypothesis is depicted within Figure 2.

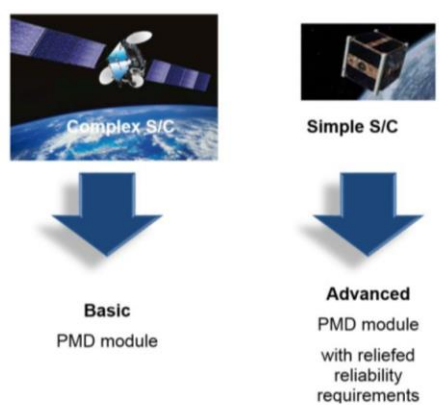

Figure 2: Applicability for advanced PMD module with autonomous removal triggering.

The autonomy option offers the advantage of safe and robust removal even if the host spacecraft is malfunctioning. If the control over the spacecraft has been lost, an autonomous removal by the PMD module requires first, that the necessity to remove (i.e. the removal triggering) is diagnosed by the spacecraft.

Second, the autonomous removal requires a system with all capabilities (comms, AOCS, OBC, etc.), which are already planned for the basic removal subsystem.

Furthermore, the autonomy is enabled by low power requirement and short operation time for the de- or re-orbit procedure. Figure 3 shows the developed scheme of three advanced autonomy levels of increasing autonomous capabilities. Each higher level includes the functions of the lower level.

4. Status detection

4.1 Detectable Symptoms

A high level system analysis has been performed in order to assess, which symptoms of a host S/C indicate a fault or failure AND could be detected by the PMD module either by monitoring and analysing telemetry of the host S/C (advanced level 1) or by interpreting data of own measurements (advanced levels 2 & 3).

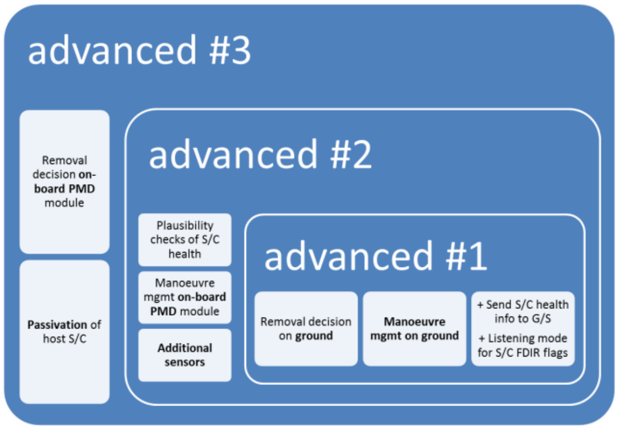

Figure 3: Autonomy concept - Definition of three advanced levels.

Symptoms that can only be detected by telemetry analysis of host S/C:

- No command received from ground
- No transmission to ground
- Error words or flags exist
- FDIR actions triggered
- S/C and AOCS mode and sub-mode other than nominal
- Duty cycles of actuators non-nominal
- On/off settings, status and health information of sensors and actuators

Symptoms that could be detected by PMD module independently using an additional sensor package (or the respective AOCS sensors that are available in some design cases):

- Not sufficient power available (since PMD module is powered by host S/C during its nominal operational lifetime)
- Operational or survival temperature range exceeded
- Excessive angular and/or rotational rates
- Change in magnetic field of host S/C (this one is subject to an on-going research project at the institute: can different operational modes of S/C units be detected by measuring their emitted magnetic field?)

4.2 Sensors for status detection

Typical sensors for space application have been investigated with respect to their possible contribution to detecting the above identified symptoms (refer to Table 3).

In order to find their most suitable combination for the TeSeR application, a systematic trade-off has been performed. Six criteria – low power demand, high applicability in all orbits and to S/C sizes, low complexity, additional benefit of the sensor e.g. for navigational purposes, mass and cost – have been defined and weighted as shown in Table 1.

Table 1: Weighting of trade parameters.

	Power	Applicability	Complexity	Benefit	Mass	Cost	Line Sum	Weight Factor: Line Sum / Total		Weight Factor: Line Sum / Total in %
Power	1	1	1	1	0.5	1	5.5	0.2619		26.19%
Applicability	0	1	0	0	0	1	2	0.0952		9.52%
Complexity	0	1	1	1	0	1	4	0.1905		19.05%
Benefit	0	1	0	1	0	0.5	2.5	0.1190		11.90%
Mass	0.5	1	1	1	1	1	5.5	0.2619		26.19%
Cost	0	0	0	0.5	0	1	1.5	0.0714		7.14%
Total							21			100.00%

For example, power is judged equally import than mass and therefore, the value 0.5 is filled in. The last column shows the normalized weight factors for each criteria. As can be seen, power and mass are most important, followed by applicability and complexity, whereas cost and benefit are rated lower.

For each criteria, the sensor options are evaluated against one another using again the pairwise comparison technique. This way, a figure of merit for each sensor regarding each criteria can be calculated (these specific details can be found in [2]). Finally, the trade-off evaluation is performed by calculating a ranking of sensors from the figures of merit and weighting factors. The result is given in Table 4.

Star sensors are probably too expensive and too heavy, the accuracy they offer in return is not considered necessary within the scope of TeSeR.

Horizon Sensors are not considered further, because they seem to have a limited lifetime with a comparably high mass and power consumption at the same time – resulting in a respectively low ranking within the trade-off.

Compared to Coarse Sun Sensors, Fine Sun Sensors offer better performance (which is not needed) at higher cost, mass and complexity and are hence not considered further.

Clearly, the high rating of mass and power lead to the (MEMS) gyros being the most preferable sensors to be flown on the PMD module. Coarse sun sensors are also rated highly due no power consumption, low mass, cost and complexity.

TeSeR has modest accuracy requirements and the PMD module architecture shall be simple and applicable for all target orbits. Therefore, a classical sensor combination of three MEMS gyros with three coarse sun sensors (one for each axis) is proposed. That reflects also the results of the trade-off table, where gyros (rank 1) and coarse sun sensors (rank 2) are considered to add a great benefit to the PMD module with low power consumption, mass and cost at the same time.

In addition, a GPS receiver with at least two antennae is proposed. Its overall score is only half of the gyros, but it would add nicely to the coarse sun sensor that have some configurational (unobstructed field of view) and operational (not working in the Earth's shadow) constraints.

Since magnetometers might offer the unique possibility to determine whether the host S/C is still active by detecting a change in its magnetic field (which should be known to it anyway), it is also considered in further investigations (although it poses greater configurational complexity and will only work in LEO for attitude determination). Component-of-the-Shelf magnetometers have been flown successfully on-board CubeSats – these are small, cheap and offer sufficient performance.

In conclusion, this is a suitable sensor set to determine the position, attitude and velocity on-board the PMD module independently. Table 2 summarizes the resulting estimated power and mass budget.

Table 2. Budget of chosen sensor set.

Sensor	Number of Sensors	mass (max.)	Power demand
Coarse Sun Sensor	3	0.6 kg	0 W
MEMS gyros	3	0.0015 kg	0.075 W
GNSS/GPS receiver	1	1 kg	7 W
Magnetometer	1	0.15 kg	1.5 W
Total	**7**	**1.7515 kg**	**8.575 W**

5. Removal Triggering

This section refers to a PMD module of advanced level 3 (s. Figure 3; details for levels 1 & 2 in [3], level 3 includes all functions of level 1 & 2): Based on the status detection results of the host S/C (derived from both S/C telemetry and own sensor measurements as described in the previous section), the PMD module decides autonomously on-board, if and when removal is performed (not excluding the possibility to be commanded from ground).

Table 3: Summary of sensors used in space applications.

sensor	mass	Power demand	Perfor-mance	Operational temperature range	Additional consideration	cost	Orbit (LEO→GEO)	complexity	References
GNSS/GPS receiver	1 kg	7 W	Position 15 m, velocity 0,05 m/sec (1 σ)	-20°C ... +60°C	Incl. Two microstrip patch antennae; consider three for attitude determination	high	All	Low, space qualified	General dynamics: Viceroy GPS Receiver.
(MEMS) gyros	0,5 g	25 mW	"high"	–55°C ... +125 °C	COTS, flown on cubesats	Low	all	Low, COTS.	ADXRS614 from Analog Devices (CubeSats)
Coarse sun sensor	10 - 200 g	0 W (passive)	10-20 deg	-80°C ... +120°C	One per axis, not in eclipse, preferably unobstructed field of view	Low	All	Simple, reliable design	CSS by Bradford space and SPACE MICRO
Fine sun sensor	< 1 kg	≤ 200 mW per channel (2 channels)	Better than 0.05 deg	-30 °C...+65 °C	One per axis, not in eclipse, need unobstructed field of view	Medium	all	medium	FSS by Jenoptronic
magnetometer	< 150 g	<1,5 W	"high"	-40 °C ... + 125 °C	Isolation needed	Low	< 6.000 km	Low	Honeywell HMC1053 (CubeSats)
Star sensor	2 kg	12 W (including Peltier cooler)	< 1 arcsec	-30 °C ...+ 60 °C	Slew rate < 0,3 deg/sec	High	all	High	Sternsensor Astro APS ba Jenoptronic.
Horizon sensor	2,5 kg	4 W	0.1 deg	-30° ... +60°C	Unobstructed field of view needed, lifetime in LEO/GEO limited	high	< 140.000 km	medium	IRES by Finmeccanica

Table 4. Sensor trade evaluation.

Sensor Trade-Off		GNSS/GPS receiver		(MEMS) gyro		Coarse Sun Sensor		Fine Sun Sensor		Magnetometer		Star Sensor		Horizon Sensor	
Trade Criteria	weighting	unweighted	weighted	unweighted	weighted	unweighted	weighted	unweighted	weighted	unweighted	weighted	unweighted	weighted	unweighted	weighted
Power	26%	0.0714	0.0187	0.2143	0.0561	0.2143	0.0561	0.2143	0.0561	0.1429	0.0374	0.0357	0.0094	0.1071	0.0281
Applicability	10%	0.1071	0.0102	0.2321	0.0221	0.1964	0.0187	0.0893	0.0085	0.1964	0.0187	0.0893	0.0085	0.0893	0.0085
Complexity	19%	0.1250	0.0238	0.2143	0.0408	0.1964	0.0374	0.1071	0.0204	0.1786	0.0340	0.1071	0.0204	0.0714	0.0136
Benefit	12%	0.2321	0.0276	0.1964	0.0234	0.1607	0.0191	0.1071	0.0128	0.1964	0.0234	0.0536	0.0064	0.0536	0.0064
Mass	26%	0.1250	0.0327	0.2500	0.0655	0.1964	0.0514	0.1250	0.0327	0.1964	0.0514	0.0714	0.0187	0.0357	0.0094
Cost	7%	0.0893	0.0064	0.2500	0.0179	0.1964	0.0140	0.1786	0.0128	0.1607	0.0115	0.0357	0.0026	0.0893	0.0064
Total		0.7500	**0.1195**	1.3571	**0.2258**	1.1607	**0.1969**	0.8214	**0.1433**	1.0714	**0.1764**	0.3929	**0.0659**	0.4464	**0.0723**
Ranking		5		1		2		4		3		7		6	

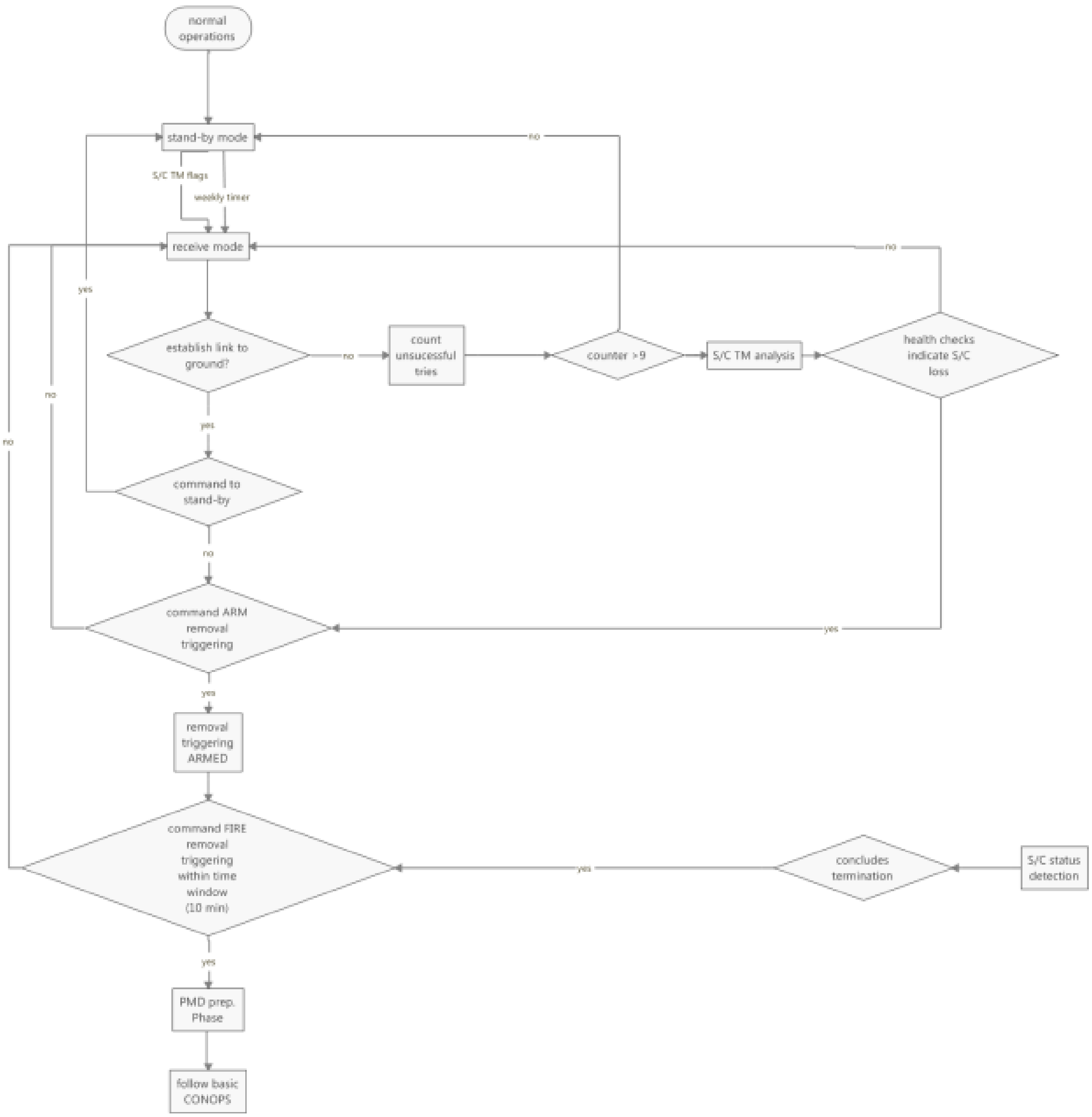

Figure 4. Autonomous removal triggering strategy of PMD module, advanced level 3.

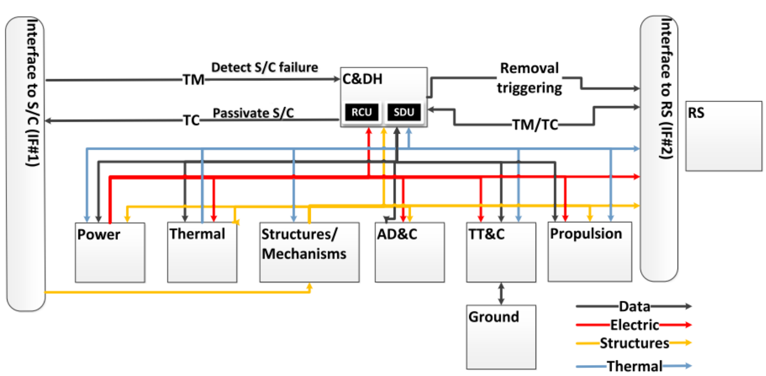

Figure 5. Functional architecture of PMD module advanced level 3.

The respective considerations are:

- Try and establish link to ground station.
- If link to ground cannot be established after 10 weeks (operationally, an appropriate time frame for host S/C recovery by ground operators from a serious fault or failure), perform plausibility checks of S/C TM for critical failures in RCU.
- Perform own diagnosis using sensor package implemented in dedicated status detection unit (SDU).
- If both units come to a terminal diagnosis independently, removal is triggered and performed autonomously on-board the PMD module.

Figure 4 shows the respectively derived strategy for autonomous removal triggering.

The PMD module is enabled to command the passivation of the host S/C by executing pre-defined passivation procedures for a host S/C that is designed to be passivated.

Compared to the basic version, there are additional TM/TC interfaces between the host and the PMD module via standardized interface IF#1 that will communicate with the command handling unit of the host S/C and use the anyway available data connections on-board the host S/C to command all subsystems, e.g. for their passivation. Figure 5 shows the respective functional architecture of a PMD module of advanced level 3 that supports the proposed removal triggering process.

The RCU and SDU will evaluate the TM of the host and also own measurements w.r.t. health status and trigger the removal operations in case of a mission loss.

For example, loss of telemetry capability of the host S/C (e.g. telemetry distribution unit or digital telemetry unit) would be a trigger for execution of the emergency mission termination procedure that includes the (reversible) passivation of the host S/C, the triggering of the removal preparations by the PMD module and the removal operations by the removal subsystem.

6. Passivation

The passivation of the host S/C is a crucial aspect before its removal by the PMD module and shall prevent its accidental break-up, which would cause even more space debris. This chapter gives the definition of passivation and summarizes the most frequent technical solutions for each passivation step.

An analysis about the possible passivation measures for the host S/C from the PMD module with and without additional hardware and consequences with respect to the successful removal, if passivation fails, is conducted and presented. The passivation measures to be taken for the PMD module itself conclude the section.

6.1 Definition of passivation

Citing the French Space Operations Act (but basically, all respective standards agree on the definition), [18] & [19],

"The system must be designed, produced and implemented such that, following the disposal phase:

- *All the on-board energy reserves are permanently depleted or placed in such a condition that they entail no risk of generating debris [by S/C explosion],*
- *All the means for producing energy on-board are permanently deactivated"*

This formulation does refer mainly to the propulsion and electrical power subsystems, to which are related the major part of ESA & NASA satellite break-ups in orbit (see Figure 6 of [5]). The data used for this statistic include spacecraft break-ups from 29 June 1961 till 22 January 2013. Since 1957, [5] cites at least 220 known break-ups in orbit.

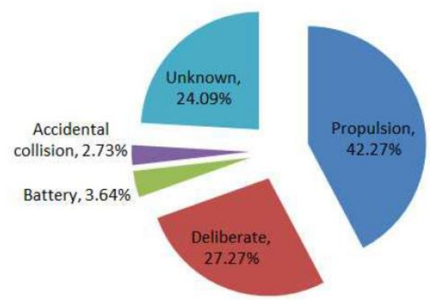

Figure 6. Cause of in-orbit satellite break-ups (ESA & NASA sources, [5]).

As can be seen in this figure, deliberate break ups are believed to account for more than 20 % of all spacecraft break-ups. Historically, S/C have been broken up deliberately for structural testing, to destroy sensitive equipment so it would not be recovered by hostile forces and in antisatellite weapon tests. Fragments from these intentional break ups in high orbits (> 600 km) remain in orbit for thousands of years or more.

This figure shows also, that passivation of the propulsion system is mandatory in mitigating new space debris, since this subsystem caused more than 42 % of all known break-ups.

IADC [7] is a bit more specific in its requirements and defines passivation as

… "the elimination of all stored energy on a spacecraft or orbital stages to reduce the chance of break-up. Typical passivation measures include venting or burning excess propellant, discharging batteries and relieving pressure vessels."

Ultimately, the ESA Space Debris Mitigation Compliance Verification Guidelines [20], provide a table that lists in very detail the subsystems, components and respective passivation measures to be taken.

The French Space Operations Act [18] establishes a transition period for spacecraft launched before 31/12/2020. After this day, all S/C launched or being operated from French territory need to provide means for EOL passivation of all energy sources.

ESA Space Debris Mitigation Compliance Verification Guidelines, dated from 09/02/2015, [20] offers an interpretation of the standards as follows:

The passivation is required for all S/C that are not directly re-entering the Earth's atmosphere in a controlled manner for disposal, i.e. S/C that are de-orbited within the 25 years time span and S/C that are re-orbited and parked in graveyard orbits. Also, none of the standards requires a fail free passivation.

The following conclusions can be drawn for the TeSeR development from the above considerations:

- For the TeSeR timeframe, it is assumed, that S/C that apply the PMD module technology in the future are designed to being passivated at the beginning of their decommissioning.
- The PMD module is to be passivated itself after having performed the removal operations unless in case of a direct, controlled atmospheric re-entry from LEO.
- The PMD module is to be passivated if it remains unused in orbit.

The second and third statements are quite important, since the PMD module is supposed to be attachable to any S/C in any Earth orbit. In addition, passivation of the host S/C is essential for its successful removal. E.g. an active AOCS or propulsion system could resist the de-orbit procedure.

6.2 Passivation of subsystems – why and how.

The current trend in spacecraft design goes towards a new mindset and new technology developments with respect to proper disposal including the passivation of spacecraft. This development is surely triggered by the guidelines and standards of the space agencies. The number of publications to that regard has increased notably within the last two years. Possibilities of electrical passivation are being investigated, but also the propulsion system passivation is currently being developed further.

The following section will list all components and subsystems on-board a S/C that might pose an explosion risk; it will summarize possible passivation means and associated effects on the S/C.

6.2.1 Propulsion system and fluids passivation

Reason for passivation

One of the most discussed subsystems to be passivated is the propulsion system of a spacecraft, since the explosion risks are obvious: The tanks contain pressurized fluids and/or propellants that pose a high risk of explosion, once the thermal control is no longer available and the tanks potentially heat up. Furthermore, the tanks could burst due to a hypervelocity debris impact or the long-term propellant decomposition could lead to overpressure.

An additional risk for GEO S/C is also the leakage of not disposed propellant or pressurant and subsequent un-intentional orbital evolution. Such an example gives the TDF2 S/C in 1999, see [27] & [29] for details.

Passivation objectives & means

The objective is clearly to drain propellants as well as pressurizing gas and depressurize all hardware. Furthermore, the orbital lifetime for LEO S/C should be limited after mission completion.

Most common techniques include first, the usage of left-over propellant for additional burns or longer burns in order to lower the orbit (e.g. lower perigee in case of LEO S/C) or putting the S/C into its graveyard orbit (GEO S/C) and deepen the propellant draining at the same time.

Afterwards, the still remaining propellant is depleted through the nozzles, if possible. Most S/C allow for this procedure even without being built for it. According to the tanks content, different phases will follow one another:

- A bi-propellant phase with bubbles for one propellant at given thruster
- A gas phase when liquids are run out at all thrusters
- An intermediate phase between these two phases, which is difficult to define and as difficult to predict as the transitions between the phases.

An exception is the venting of unused helium pressurant from the spacecraft – if not build for it, there is usually no means to empty or depressurize it [23]. The same is true for tanks which employ a bladder between propellant and pressurant [22].

Anyway, future S/C will add dedicated fluidical H/W for the proper ejection of propellants and pressurants like helium or nitrogen. There are several studies on-going to that extent: [19] proposes e.g. additional pyro-valves or micro-perforators, [21] developed a momentum-free venting device for pressurization tanks operating with helium. Also, an additional (bypass) valve in the fill-and-drain line is a good option.

All valves are to be left in the open position or are to even to be blocked in the open position by additional means (e.g. add-on pyro-technical devices like rods). This way, the risk of fuel that is trapped in fuel lines is minimized. Furthermore, a characterization of reaction control thrusters for low inlet pressure would allow a better passivation.

All of these additional devices should be robust and reliable after a long orbital lifetime.

Induced Risks

- Trapped propellant in fuel lines might cause them to rupture upon heating up.
- The depletion of propellant might influence the final orbit of the S/C in an unexpected way and/or produce unwanted torque, see e.g. [27].
- Generation of droplets and/or potential freezing of the outlets by venting propellant, see e.g. [22].
- In-advertent triggering of additional pyro-technique devices.

6.2.2 Electrical power subsystem

Reason for passivation

Overpressure in charged batteries can lead to battery rupture and potential spacecraft break up. Therefore, regulations aim at the battery being fully discharged at the End Of Life. The energy of the solar array shall neither be transmitted to the batteries nor to any active equipment.

Passivation objectives & means

To prevent such break-ups, designers should implement a battery management system that ensures the battery to be left in in a completely discharged state at the end of the spacecraft's functional lifetime. Additionally, the battery should be short-circuited to prevent recharging. This can also be achieved by not switching off some passive loads (i.e. instrument heaters) to ensure the battery is being discharged, a technique used e.g. in ICESat End of Mission operations [26].

In more general terms, the following strategies for power system passivation are

- Battery disconnection
- Solar array (SA) disconnection
- Solar array AND battery disconnection

For future S/C, there is a number of respective technologies being developed, for example:

- SA short circuit in dedicated external electronics box
- Bus short circuit
- Switches in series inside the PCDU to inhibit the SA current transfer to the bus
- SA harness cutting devices

Airbus investigates the modification of PCDUs so they disconnect the battery at the end of the mission and thus, reach the passivation of its S/C. Several different concepts have already been developed (see [17] and [19] for details). Also, several studies under ESA contract have been carried out and came to promising results with respect to battery discharging and disconnections of battery and solar array (see [24], [5] for summary and further reference).

It can be summarized, that there is no unique solution for electrical passivation. But, depending on the spacecraft power subsystem characteristics (bus voltage, total power generation, number of SA sections, orbit etc.), there are already a number of possibilities available that are low cost and low weight – by simply adding a relay to the power subsystem.

Note: If the S/C is not designed for being electrically passivated, it is highly probable that the battery is not meant to be disconnected from its charging circuit. In this case, electrical passivation is not possible (refer e.g. to [23]). Or at least, very difficult, refer to sec. 6.3.2 for exceptions using an indirect method.

Induced Risks

Battery rupture could remain a risk even after passivation – since there are not yet long-term data available about the behaviour of batteries 25 years in orbit without thermal control. But studies are on-going to assess the effects of radiation, temperature, state of charge and aging of the battery, e.g. within the ESA CleanSat programme, see also [24].

6.2.3 Reaction or Momentum Wheels & Control Momentum Gyros

Momentum devices like reaction wheels or control momentum gyros represent an internal energy source according to IADC [7].

They should be powered off within the passivation sequence of the S/C and their speed should be set to zero.

Ground tests in [22] confirm, that they will stop shortly after being powered off, i.e. for an angular momentum of 30 NMS and a rotating speed of 4600 rpm, the coast-down time was about 1 h. Therefore, the dissipation of stored energy in case of these wheels and gyros is solvable quite straightforward.

6.2.4 Fault Detection, Isolation & Recovery

Fault responses are to be disabled on both, nominal and redundant sides of the S/C. The system is designed to protect the S/C and keep it operational. The disabling can be achieved by patching the on-board software. There is again a unique solution require for each single S/C depending on its design. But generally speaking, the following responses are to be disabled, if applicable:

- Disable battery protection that limit battery lower state of charge
- Disable undervoltage/overvoltage protection of units
- Disable FDIR switch-on routines for RF transmitters and whole radio frequency chain
- Disable AOCS protection
- Disable fault protection routines like safe mode

Practically, this could be done by replacing all "SWITCH unit ON" commands within the FDIR being triggered by respective "SWITCH unit OFF" commands. Examples from literature can be found for the Herschel Planck telescope passivation [28] and the ICESat end of mission procedure [26].

6.2.5 Radio Frequency Chain

In order to prevent the spacecraft from being a RF source after its end of life, transmitters, modulators, any beacons and amplifiers are powered off after respective FDIR protection has been turned off.

At the same time, this measure serves to ensure that no one else can control the S/C once the operators have ceased control.

6.2.6 Pyrotechnic & Electro-explosive devices

Unused pyrotechnic charges which are designed to activate a system, but cannot cause vehicle fragmentation need not to be fired upon decommissioning. Even their accidental future firing should not result in orbital debris generation [23].

6.2.7 Heatpipes

Heatpipes are indeed high pressure devices. But studies under ESA contract could demonstrate that their probability of rupture is very low and no significant break-up could be achieved [22].

Likewise, NASA Engineers concluded in [23] that heatpipes may be left pressurized, no further passivation, i.e. depressurization, is considered necessary.

6.2.8 Mechanisms

Mechanisms as well as any rotating or movable parts are recommended by [20] to be fixed and blocked.

This measure is recommended to protect the appendages that are usually attached to the S/C by the mechanisms.

6.3 Passivation considerations of host S/C

Two cases are to be distinguished: host S/C that either are or are not designed to being passivated. For the PMD module design cases, it is assumed, that host S/C are compliant with the French Space Operations Act and come with the self-passivation ability.

To complete the analysis, a short consideration is added with regard to spacecraft that are not passivated – either because they were never designed for it or because the passivation design failed.

6.3.1 Host S/C designed for self-passivation

In the basic PMD module case, the host S/C needs to be passivated by ground operators according to its own decommissioning plan. It is considered to be designed for passivation and thus, be compliant to the space debris mitigation guidelines mentioned before.

In general, the required steps for passivating any S/C are:

1. Propulsion system passivation. Since the propellant estimation methods are still inexact, there might be some propellant left to be drained by additional manoeuvres. If no manoeuvres are considered, remaining propellant will be vented.
2. Disable appropriate fault management mechanisms.
3. Power off all non-essential equipments like scientific instruments, IRU, star tracker, heater, etc.
4. Electrical system passivation. Implicitly contains also passivation of reaction and/or momentum wheels and control momentum gyros. Optional use of some instruments heaters as passive loads for keeping the battery discharged.
5. Disable radio frequency chain.
6. Wait for confirmation if passivation is completed successfully.

Steps 4 and 5 might be switched, since without power, there will eventually be no more transmissions.

Note, that many studies consider reversible passivation options in innovative designs (e.g. [17]). This is especially relevant if a highly autonomous PMD module is applied, since the ground operators are then able to reverse a removal triggering decision made on-board the PMD module.

After the successful passivation of the host S/C has been verified by the ground operations team, the operations of the PMD module will be started.

For an impression of the related passivation timeframe: using EO-1 as an example, the passivation activities (excluding the planning) took three weeks to complete including a two week period allotted to verify that no radio frequency signal can be acquired, which verifies the successful passivation [30].

6.3.2 Host S/C not designed for self-passivation: indirect methods.

If either the passivation design has failed or the spacecraft has not been designed for self-passivation, there are only few operational work-around options with system level implications to achieve a minimum of passivation. Two examples will be given to demonstrate, that the required system level knowledge for such "operational passivation" cannot be offered on-board any (autonomous) PMD module.

Example 1: Electrical passivation by indirect method

In the PROBA 3 case, see [25] for reference, on-board software patches to have been implemented successfully to

- lower the batteries maximum state of charge to ~ 5-10 % (assumed to be safe) and
- to disable respective FDIR actions for battery and under-/over-voltage protection at the same time

in order to passivate a S/C electrically without being designed for it.

A similar method was implemented for CloudSat [4]: a low setting of the voltage-temperature curve was implemented in combination with safe mode triggering (turn off all non-essential loads and fix solar array position). The result was low power generation that was consumed by intentionally left on passive loads like instrument heaters, for example.

Example 2: Propulsion/tank passivation

There are some examples with regard to propellant depletion and thus, propulsion system passivation for S/C that were not originally designed for it, e.g. the ERBS LEO science S/C from NASA, launched in 1984 into a 611 km, 57° inclination circular orbit and successfully decommissioned in 2005. After estimating the remaining fuel on-board the S/C (which was hard to do, since there were no records of all burns of the last 21 years available), and taking into account severe subsystem degradations, there were 4 burns planned to empty the propulsion tanks and thus, minimize the explosion risk of the S/C.

In the end, continuous reassessment of the S/C behaviour, its resulting attitude, and remaining propellant during the burns resulted in a total number of >70 burns over five weeks of operations (Sept. 8th to Oct. 13th, 2005) with the result of ~490 km perigee height.

Problems were also the unpredictable behaviour of the propulsion system with un-nominal low pressure which resulted in an unstable system with unexpected orbital evolutions due to outgassing or very low thrust. See [31] for details. Other examples would be Spot1 [32] and Eutelsat 2 FM4 [33].

6.4 Passivation considerations of PMD module

In most of the cases, the PMD module itself needs to be passivated in all application scenarios other than the direct re-entry from Low Earth Orbit using the solid rocket motor. In addition, in the unexpected case the PMD module remains unused and no removal of the host S/C is performed, the PMD module should also be passivated according to passivation regulations.

A general system level approach is necessary to prevent the respective potential break-up of the PMD module itself. The proposed approach is to

1. Determine all potential sources of stored energy remaining on the PMD module.

Due to the required scalability of the PMD module to account for applicability on S/C of different sizes and different orbit as well as accommodation of three different removal subsystems, a modular design approach is chosen to define the suitable PMD module for each individual scenario. Each PMD module version has to analysed carefully to determine potential energy sources of stored energy, e.g. if there is a secondary battery on-board or reaction wheels.

2. For each identified source, provide a method of dissipating the stored energy in a benign manner.

This step is required early in the design phase – in the TeSeR time frame, the right time is actually right now. This way, passivation means can be accounted for in a low cost and low weight manner.

3. Activate these means at the end of the PMD modules functional lifetime, in other words, passivate the PMD module in all scenarios other than the direct re-entry from LEO.

As part of the operational concept, the following consideration are to be taken into account for each PMD module passivation:

- Passivation activation must be one failure tolerant regarding its unintentional activation w.r.t. all components involved
- The passivation function is allowed to fail in passivating the PMD module (see sec 4.2), i.e. it is not required to implement one failure tolerant electronics (although it should be considered).
- The passivation could be reversible by design.
- In LEO, the passivation should be able to offer reliable and robust operations for 25 years in orbit.
- In GEO, the passivation units should operate reliable and robust after the S/C mission design time of 15 years.

7 Summary & Conclusions

Especially important for the TeSeR application are the following conclusions w.r.t. passivation: Within the TeSeR timeframe, it is assumed, that S/C that apply the PMD module technology in the future are designed to being passivated at their decommissioning. The PMD module is to be passivated itself after having performed the removal operations unless in case of a direct, controlled atmospheric re-entry from LEO.

Removal triggering is explained and autonomous options and fields of applications are investigated. The related main conclusions are: Removal triggering of a S/C will most likely involve a human operator in the loop for the foreseeable future. In case of mega-constellations, autonomous removal is a great option especially from a cost point of view (operational cost for traditional health monitoring and removal process vs. reduced reliability for autonomous removal).

A dedicated section summarizes an extensive literature survey about spacecraft subsystem passivation methods, gives an overview of the state of the art and on-going innovations. The main conclusions for passivation options of host and PMD module are: Host S/C that are designed to be passivated can also be passivated by an autonomous PMD module (advanced level 3). Host S/C that are not designed to be passivated are very difficult to be passivated autonomously using an indirect method.

Finally, an advanced autonomy concept including corresponding functional architecture and operational strategy was designed and presented.

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