A satellite dedicated decommissioning device based on solid rocket motor technology

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Abstract

The problem of space debris is becoming an increasing concern among the space community and both remediation and mitigation measures were identified in order to guarantee a sustainable future for space activities. The active debris removal approach focuses on the recovery and decommissioning of defunct satellites and rocket bodies that are already in space, necessary to control the growth in the debris population and to limit the risk to active satellites. Up to today, different concept studies are on-going and the identified solutions are strongly hampered by long development time and high costs involved, together with legal and political issues associated to the removal of defunct satellites already in orbit. Mitigation measures are characterized by lower development time and costs and consequently considered to reach TRL 9 in a lower time frame. This paper presents a dedicated and independent de/re-orbiting propulsion system developed by D-Orbit for a quick and safe satellite disposal maneuver of the satellites at the end of life, called D3. The decommissioning solution here presented is based on solid rocket technology, thus allowing a direct re-entry for LEO satellites and direct re-orbiting for MEO and GEO satellites.

1 Acronyms

Acronym	Item
A(D)CS	Attitude (Determination) and Control Subsystem
C/D	Charge/Discharge
CCU	Command and Control Unit
D3	D-Orbit Decommissioning Device
EED	Electro Explosive Device
EES	Electro Explosive Subsystem
EoL	End of Life
EPS	Electric Power Subsystem
EPS-PC	Power Conditioning Unit
FC	Fire Circuit
FCC	Fire Control Circuit
GEO	Geostationary Earth Orbit
GNSS	Global Navigation Satellite System
I/F	Interface
LEO	Low Earth Orbit
MEO	Medium Earth Orbit
OBC	On-Board Computer
PFI-ED	Data Interface to Platform
PFI-EPI	Power Interface to Platform
SAD	Safe and Arm Device
SW	Software
TAU	Terminal Attitude unit
TT&C	Telemetry, Tracking and Command
TVC	Thrust Vector Control
TX/RX	Transceiver

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2 Introduction

2.1 End-of-Life Decommissioning Requirements

Half a century into the space age, the space community is now facing a ever-growing threat to the future sustainability of mankind's access to space: space debris. With more than 300 000 of uncontrolled objects bigger than 1 cm orbiting below 2000 km [1] (identified by IADC 10[2] as the limit of the LEO protected region, see Figure 1), the "space debris problem" is one of the major systemic issues the space community is asked to face and solve in the next decade.

In the past few years, [2]-[9] agencies and international institutions started issuing regulations are requirements (e.g. the famous "French Law") which, at different levels, require the spacecraft operators and manufacturer to employ strategies, behaviors and design actions to reduce, and eventually stop, the systematic increase of concentration of uncontrolled objects in space (i.e. mitigation actions).

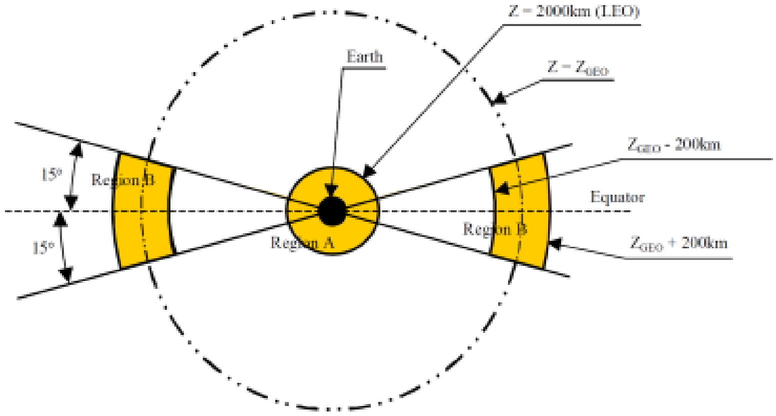

Figure 1: IADC protected regions in LEO and GEO [1].

In extreme synthesis, these regulations require the space assets to be either de-orbitred within 25 years from satellite's EoL, or re-orbited on a graveyard orbit which assures the defunct satellites not to intersect any sensible region (GEO, LEO, or operative MEO, see Figure 1) within 100 years from EoL. Compliance to these requirements is usually to be achieved early in the design phase (e.g. according to ECSS, a Space Debris Assessment shall be conducted by the design authority during phase A) and require great engineering effort and strong impact on the design of the system.

As a consequence to the arise of these new requirements and guidelines, a great deal of active (i.e. based on a propulsion system) and passive (i.e. propellant-less, using atmospheric drag, solar radiation pressure etc.) solutions for satellite decommissioning have been proposed, including, but not limited to:

- Solar sails, using solar radiation pressure and, in LEO applications, atmospheric drag
- Inflatable balloons, exploiting atmospheric drag to lower the orbital altitude and, eventually, driving the satellite into the atmosphere
- Tethers (both electromagnetic and not)

All of these solutions, however, have narrow applicability (e.g. balloons can't be used about few hundreds of km in altitude) and are still at very low TRL, with actual feasibility and efficiency still to be proven.

Since the beginning of its activity in 2011, D-Orbit is developing a dedicated decommissioning device (called D-Orbit Decommissioning Device, or *D3*) which, based on the reliable and well-known solid propulsion technology is deputed to provide the propulsive maneuver to the spacecraft during decommissioning phase. Being scalable, modular, and environment-independent, the D3 is applicable in all significant cases of spacecraft orbiting around Earth (or other celestial bodies): in the following chapters, the design of the D3 will be presented and its subsystems and features described.

2.2 Velocity Increment (Δv) Budget

Generally speaking, guidelines and requirements on space debris mitigation oblige the operator of space asset to move the spacecraft away from the protected regions either by re-orbiting, or by deorbiting. This requirements therefore translates into a required increment (or decrement) of the orbital speed, thus a required Δv to be applied to the spacecraft. Here follows the computation of such a velocity variation requirements for LEO, MEO and GEO cases.

2.2.1 Low Earth Orbit

In case of LEO satellites, the general approach is to decelerate the spacecraft, lowering the perigee until the atmospheric drag is strong enough to drive the satellite into either an uncontrolled (e.g. 25-years long) or a controlled and direct re-entry.

Velocity decrement requirements for deorbiting from LEO are depicted in Figure 2.

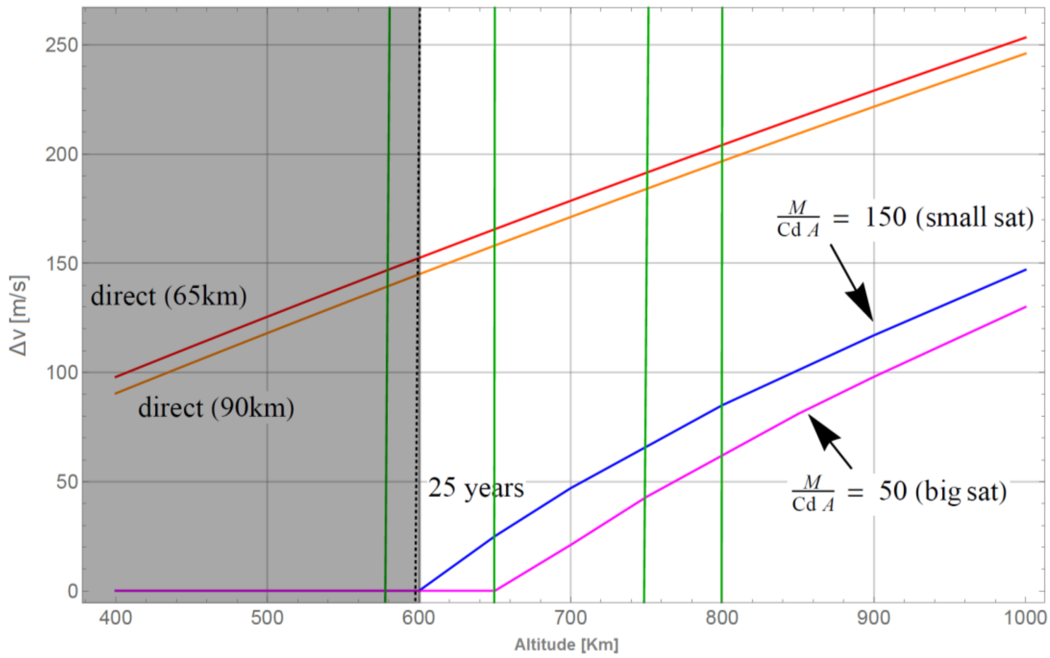

Figure 2: LEO Δv requirements for deorbiting.

Red and orange lines indicate the Δv required for direct reentry for transfer orbits with perigee of 65 km and 90 km, respectively. Blue and magenta lines represent the required velocity decrement for assuring a 25-years reentry, for high and low ballistic coefficient[2], respectively. Green lines represent the two most densely-populated orbital altitudes (between 580 and 650 km, and between 750 and 800 km) of the LEO region.

Spacecraft in the grey region (altitude below 600 km) do not require any propulsive maneuver to comply with the 25-years rule, however, they are still required to perform a direct and controlled deorbiting if the total casualty risks is higher than 10^{-4}, as typical for big LEOsats in an event of uncontrolled re-entry. Requiring the spacecraft to achieve a direct re-entry excludes from the table all passive mitigation options (such as tethers and balloons), requiring an active maneuver.

2.2.2 Medium and Geostationary Earth Orbit

Currently, MEO and GEO satellites decommissioning specifications require the spacecraft to be re-orbited on a graveyard orbit which assure the defunct satellites not to intersect any sensible region (GEO, LEO, or operative MEO) within 100 years from EoL. For both MEO (Galileo GNSS) and GEO, we can identify the graveyard orbit as a circular orbit some 300 km [3][10][11][12] above the nominal operative orbit.

[2] With ballistic coefficient defined as in figure: $BC = M_{SAT} / (C_D A)$

The simplest decommissioning manoeuver is similar to a Hohmann transfer between the initial and the target orbits for minimizing the required Δv. As such, two fires are required. The thrust pulses are delivered in the direction of the orbital velocity vector. The overall decommissioning orbital raise lasts for half period of the transfer orbit, i.e. about 6 hours for MEO and 12 hours for GEO.

In general, Δv requirements for re-orbiting from nominal MEO (altitude 23222 km, ref. Galileo GNSS Constellation operational orbit [10][11][12]) and GEO (altitude 35786 km) are reported in Table 1 and Table 2, respectively.

	Δv [m/s]
Apogee Raise	9.24
Circularization	9.22

Table 1: Δv Budget for MEO (23222 km altitude, ref. Galileo) Satellite Decommissioning

	Δv [m/s]
Apogee Raise	5.45
Circularization	5.44

Table 2: Δv Budget for Geostationary Satellite Decommissioning

3 Decommissioning Device Design

3.1 Architecture and Block Diagram

In its standard configurations, the D3 can provide one (Single-Pulse), two (Dual-Pulse), or multiple (Clustered) propulsive impulses, implementing a Single or Double pulse propulsion architecture, respectively.

From the highest level possible, the D3 is constituted by three main elements:

- The D3 Brain, including two redounded control chains, a TT&C subsystem, and the interfaces towards the platform. Each control chain is constituted by a Command and Control Unit (CCU), plus, for each pulse of the propulsion subsystem, a Fire Control Circuit (FCC) and an Electro-Explosive Subsystem (EES).
- The Motor (or motors), based on solid rocket motor technology, to provide the propulsive impulse.
- The Terminal Attitude Unit, or TAU, which includes a sensors suite for attitude determination and two actuation subsystems to provide the two functionalities: a) to allow the D3 to recover the attitude control in case of satellite malfunctioning, b) to correct eventual thrust misalignment and satellite CoG shifting by using a Thrust Vector Control system.

Featuring these subsystems, the D3 configures as an independent decommissioning device capable of removing a defunct satellite in all practical cases, even if the host platform is completely malfunctioning and non-communicating with ground.

Redundancies in the D3 Brain allow the system to be single-point-of-failure free for both safety and reliability, with computed predicted reliability exceeding 0.999 during the decommissioning phase.

3.1.1 Single Pulse D3

In Figure 3 is reported the block diagram of the D3 with single-pulse propulsion system. This configuration is suitable for LEO applications, either for controlled (direct) or uncontrolled reentry.

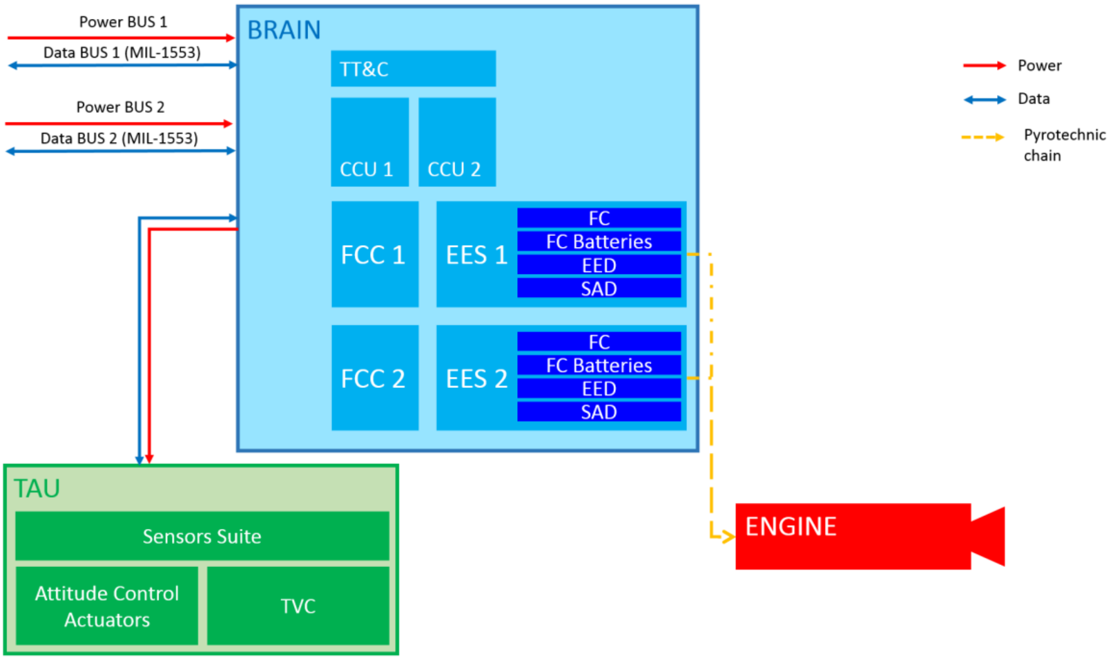

Figure 3: Single Pulse D3 block diagram

3.1.2 Dual Pulse D3

In Figure 4 is reported the block diagram of the D3 with dual pulse propulsion system. This configuration is suitable for re-orbiting applications, such MEO and GEO.

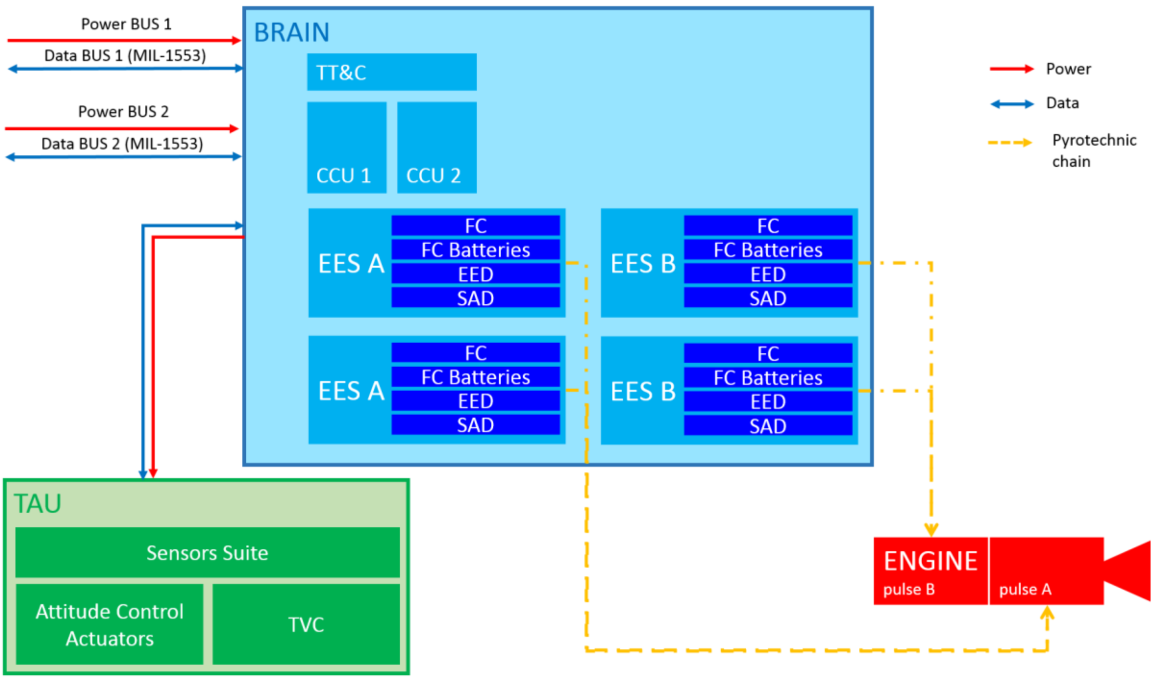

Figure 4: Dual Pulse D3 block diagram

3.1.3 Clustered D3

A third version of the propulsive subsystem currently under development implements a cluster of single-pulses motors, to form a “thrust pack”. This configuration, which uses the same control electronics of the other two, exchanges extra dry mass for augmented flexibility (e.g. multiple-maneuver deorbit/reorbit, more compact envelope when high total impulses are required).

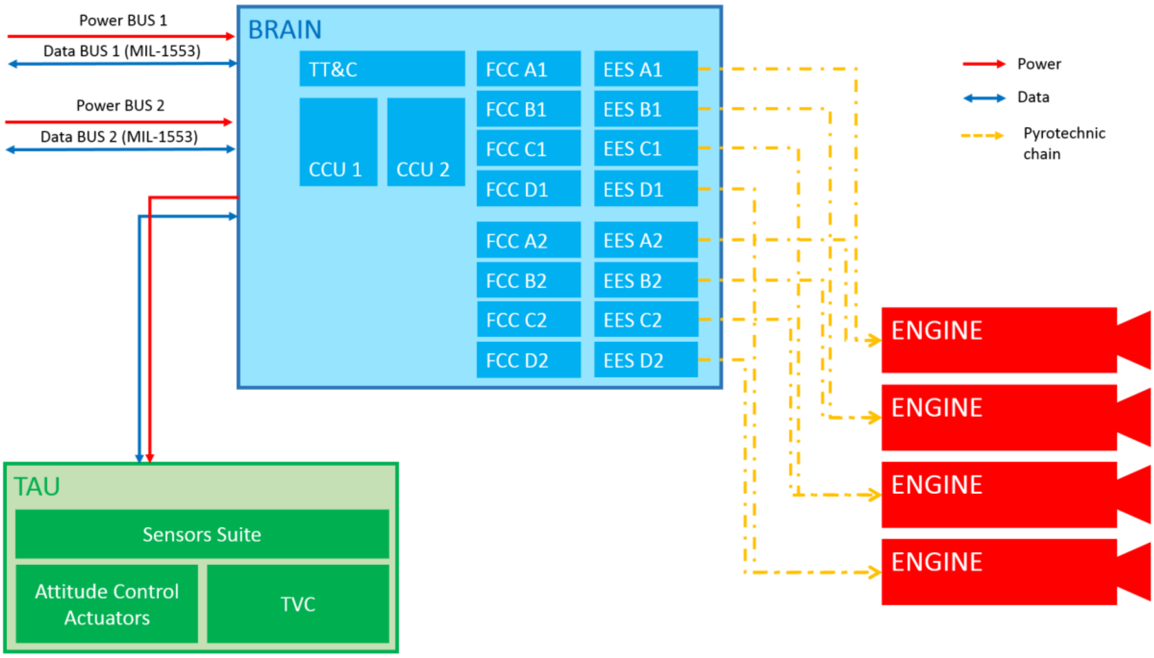

Figure 5: Clustered D3 block diagram with 4 Single-Pulse SRMs

3.2 Subsystems Description

3.2.1 D3 Brain

All the electronics of the device is contained in a single box, called *D3 Brain*, fitted on the top of the propulsion assembly. The Brain features two hot-redundant control chains, each including the following units:

- Command and Control Unit (CCU), including an On-Board Computer (OBC) and Electric Power Subsystem (EPS)
- One Firing Command Circuit (FCC) with Electro-Explosive Subsystem for each pulse to be delivered.

Also, shared between the two lines, there is a Telemetry, Tracking, and Command Unit (TT&C) and a TAU interface. The D3 Brain block diagram is reported in Figure 6.

The OBC is deputed to manage and control the behavior of all the D3 modules, and is based on an ASIC microprocessor running the RTEM operating system. A low-power operating mode allow the OBC to run the watchdog function for the host satellite with minimal power drain during the operative life of the platform.

The EPS manages the power interface with the platform, regulate the charge and discharge of the secondary batteries, and regulate and distribute the voltages to all the modules of each CCU. The D3 brain features two distinct battery arrays:

- A primary (non-rechargeable), high-capacity battery array, to power the decommissioning operations
- A secondary (rechargeable) battery pack to provide power buffer capabilities to the D3 during the platform operative lifetime.

Both batteries implement flight-proven Lithium-based chemistry.

For each motor pulse, a Fire Control Circuit manages the inputs and safety provisions, controlling an Electro-Explosive Subsystem featuring an electro-mechanical Safe-And-Arm device. The overall design of the D3 exceeds safety standards (i.e. MIL-STD-1556), implementing four barriers with two different technologies. Each EES also feature a non-rechargeable, high-current battery to provide the ignition current to the igniter.

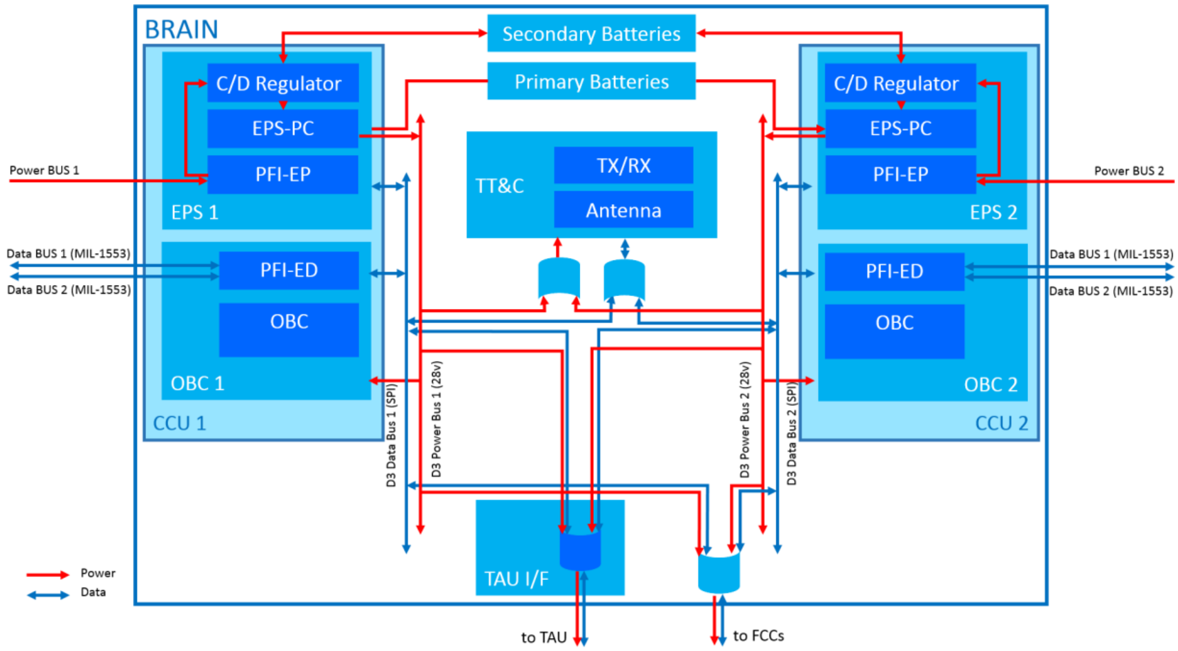

Figure 6: D3 Brain block diagram, excluding FFCs and EESs, which are physically outside the electronic box and connected to the motor(s)

3.2.2 Propulsion

The D3 propulsion subsystem implements a Solid Rocket Motor technology to deliver in an efficient and reliable way the propulsive impulse(s) to the spacecraft (and hence the Δv) required for the decommissioning.

The propulsion subsystem of the D3 is available in three single-pulse classes and two double-pulses (Table 3) to cover all the most common cases of applications both in LEO, MEO and GEO. The typical applicative cases for each class are reported in Table 4.

The SRM technology allows some flexibility to the propulsion subsystem (quantifiable in ±20% of the total impulse), which can be tuned to the specific case without the need of a requalification of the motor.

Class	Architecture	Nominal Impulse [KNs]
S19	Single Pulse	19
S45	Single Pulse	45
S65	Single Pulse	65
D14	Dual Pulse	14
D42	Dual Pulse	42

Table 3: Propulsion Subsystem Classes

Higher impulses can be achieved by clustering single-pulses motor. Nominal mass reported in Table 3 refers to propulsive subsystem in nominal impulse configuration and include the EES(s) for the safe-and-arming of the SRM.

Class	Typical Applications
S19	- 25 yrs re-entry of 200 kg satellite at 800 km orbit - Direct re-entry of 150 kg satellite at 650 km orbit - 25 yrs re-entry of 850 kg satellite at 650 km orbit
S45	- Direct re-entry of 200 kg satellite at 800 km orbit - 25 yrs re-entry of 800 kg satellite at 800 km orbit
S65	- 25 yrs re-entry of 1000 kg satellite at 850 km orbit
D14	- Re-orbit of 780 kg satellite at MEO (altitude 23222 km, cfr. Galileo) on graveyard orbit 300 km above nominal
D42	- Re-orbit of 3900 kg satellite at GEO (altitude 35786 km) on

	graveyard orbit 300 km above nominal

Table 4: Propulsion Subsystem Classes Typical Application Cases

Typical applications refer to nominal impulse. Great applicative versatility is achievable by exploiting the flexible design of the SRM.

3.2.3 Terminal Attitude Unit

The Terminal Attitude Unit (TAU) is an optional module deputed to delivering the following functions:

- Stabilize, recover the attitude of a satellite with no attitude control (e.g. malfunctioning satellite) and provide attitude pointing for the decommissioning maneuver
- Counteract potential thrust misalignment due to mounting tolerances, uncertainties in satellite's CoG position, ignition transients, etc.

The two functions are delivered by means of two actuators suites:

- A suite of cold gas thrusters for the attitude recovery and control function;
- A thrust vector control system

A sensors suite provide the required inputs for the attitude determination used for both the TAU functions, with expected attitude knowledge performance better than 0.1 deg.

3.2.4 Software

D-Orbit Decommissioning Device software is designed in order to be modular and adaptable to different configurations. The software is developed using C and ADA languages and the underlying operative system is RTEMS. All the software components are aligned with ECSSE-ST-40C standards, with level B criticality.

The software architecture is illustrated in Figure 7. All the software modules are encapsulated and exchange information asynchronously through the main framework. The software has four main connections with external equipment, but since different equipment can be used, adapter modules are designed in order to keep the same software core running.

This modular approach allows flexibility in the choice of hardware components, allowing rapid reconfiguration, customization and delta-qualification of the product, if specific custom needs of the customer arise.

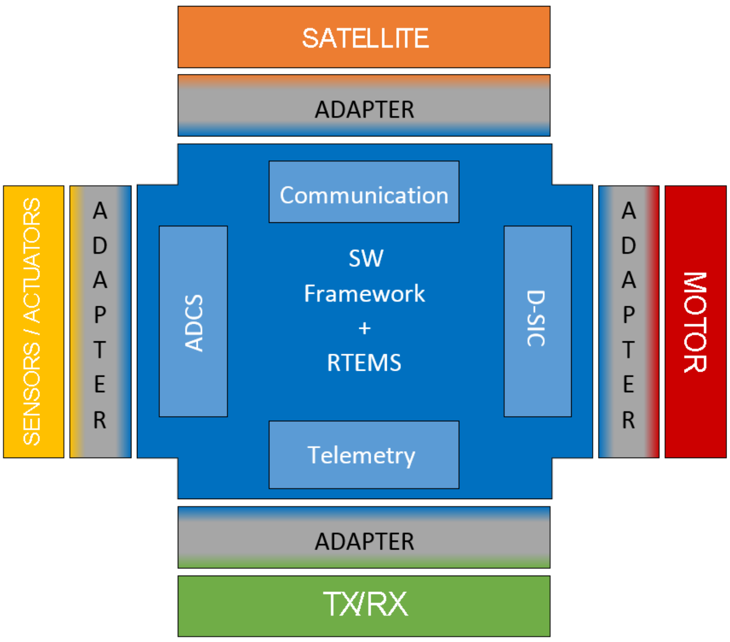

Figure 7: D3 Software Architecture

3.3 Interfaces

3.3.1 Mechanical Interface

In its standard configuration, the D3 is to be fitted along one of the principal inertia axis of the spacecraft (for best performance, the minimum inertia axis is to be preferred).

Such a design allows easiest attitude pointing operations (performed either by satellite's AOCS or D3 TAU) and highest robustness against thrust misalignment due to fitting tolerances, propulsion system transients and/or unexpected satellite CoG shifting.

The standard mechanical interface implements the well-proven architecture adopted for liquid apogee motors: four beams withstand the loads be means of their flexural stiffness and strength and connect the device to the cylindrical structural bus of the spacecraft. Alignment of the device with the spacecraft CoG is to be provided during the integration of the D3 and potential misalignments are addressed by the D3 TAU/TVC functionality.

The mechanical interface can be customized on specific structural and/or configuration requirements upon request from the customer, including, but not limited to, the possibility of separating the SRMs to respect specific layouts of the spacecraft side, or strong offset between device's longitudinal axis and spacecraft's principal inertia axes.

3.3.2 Power Interface

The D3 is connected to the satellite power buses through two (one per power bus of the satellite) electrical interfaces working at unregulated 24/28 V DC (or regulated 100 V DC), which are used also as watchdog to monitor the status of the platform.

The D3 is completely power-independent during decommissioning operations.

3.3.3 Data Interface

The D3 interfaces with the satellite bus through a serial data interface adopting MIL-STD1553, CAN and SpaceWire standards. The modular architecture of the D3 brain and software allows rapid reconfiguring of the data interface.

4 Views

Here follow a representative view of the D3 (in the case of Figure 8, the proportions are referred to the D42 class). Dimensions and masses are specified in Table 5.

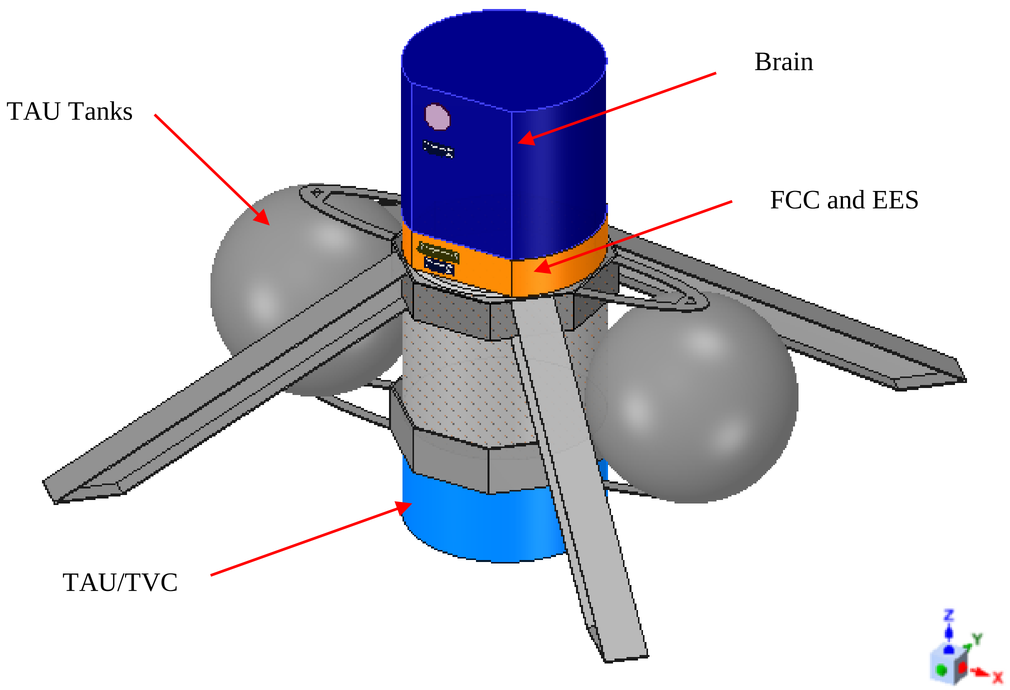

Figure 8: Isometric view of the D-Orbit Decommissioning Device (proportions referred to the D42 class)

5 Dimensions and Masses

In Table 5 are reported the dimensions of the D3 for all the product classes.

Class	Nominal Tot Mass [kg], Not including TAU and mechanical interface	Dimensions [mm], Not including TAU and mechanical interface
S19	< 19	450x450x400
S45	< 33	480x480x550
S65	< 41	500x500x620
D14	< 17	450x450x450
D42	< 31	450x450x450

Table 5: D3 Dimensions Table. All dimensions are in [mm]

The mass value reported here may vary according to the effective loading of the SRM, which in turns is depending on the actual mission and spacecraft size. As stated, TAU is not included in the budget because of the low maturity of the design of such a module.

6 Conclusion

In the present paper, an overview of the design of the D-Orbit Decommissioning Device has been given. The block diagram of the device has been presented in the three architectures of the propulsion under development (single and dual pulses, and clustered) and the description of the main subsystems followed. Featuring a number of capabilities, the D3 configures as an independent, efficient and highly reliable solution for the decommissioning of spacecraft (satellites and, in a dedicated version not presented here, launcher stages) at the end of their operative lifetime, to allow operators to be compliant with the ever-stringent requirements and regulations on space debris mitigation.

7 Reference

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