Debris Avoidance and Removal Technology Cube (*DART*^{3})

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Abstract

Space debris continues to be an increasing problem as new enterprises expand into low Earth orbit (LEO). Opportunities for both private and government entities are generating an exponential growth in satellites that are increasing the risk of space debris. In 2022, the United States took action to mitigate space debris by proposing a bill in Congress to remove nonoperational spacecraft from orbit. In the same month, the Federal Communication Commission (FCC) voted on a ruling that requires spacecraft to deorbit within five years of nonoperation. This paper explores the development of a drag modulated robot system that can meet the FCC ruling and deorbit defunct spacecraft in LEO. The robot attaches to a small satellite prior to launch and once in orbit can track, maneuver, and deorbit the satellite without any propellant. The lack of propellant lowers the risk of a catastrophic explosion while reducing size, weight, and power.

Keywords: Space debris removal, Deorbit Drag Device, Propellant Free Deorbit, SmallSats, CubeSats, Debris Avoidance and Removal Technology Cube (DART), small satellites, cube satellites

Cubo de tecnología de eliminación y prevención de escombros (*DART*³)

Resumen

Los desechos espaciales continúan siendo un problema creciente a medida que las nuevas empresas se expanden a la órbita terrestre baja (LEO). Las oportunidades tanto para entidades privadas como gubernamentales están generando un crecimiento exponencial de satélites que aumentan el riesgo de basura espacial. En 2022, Estados Unidos tomó medidas para mitigar los desechos espaciales al proponer un proyecto de ley en el Congreso para retirar de la órbita las naves espaciales no operativas. En el mismo mes, la Comisión Federal de Comunicaciones (FCC) votó un fallo que requiere que las naves espaciales salgan de órbita dentro de los cinco años posteriores a la inactividad. Este documento explora el desarrollo de un sistema de robot modulado por arrastre que puede cumplir con las normas de la FCC y sacar de órbita a naves espaciales desaparecidas en LEO. El robot se conecta a un pequeño satélite antes del lanzamiento y, una vez en órbita, puede rastrear, maniobrar y desorbitar el satélite sin propulsor. La falta de propelente reduce el riesgo de una explosión catastrófica al tiempo que reduce el tamaño, el peso y la potencia.

Palabras clave: Eliminación de desechos espaciales, dispositivo de arrastre de desorbitado, desorbitado sin propelente, SmallSats, CubeSats, Cubo de tecnología de eliminación y prevención de escombros (DART), satélites pequeños, satélites cúbicos

碎片避免和清除技术立方体（*DART*³）

摘要

随着新企业将业务扩展到近地轨道（LEO），太空垃圾仍然是一个日益严重的问题。私人和政府实体的太空机会正在使卫星数量呈指数级增长，从而增加了太空垃圾的风险。2022年，美国国会提出一项法案，将不运行的航天器移出轨道，以期减少太空垃圾。同月，美国联邦通信委员会（FCC）就一项裁决进行投票，该裁决要求航天器在不运行的五年内脱离轨道。本文探究了一种阻力调节机器人系统的开发，该系统能满足FCC的裁决并使近地轨道上报废的航天器脱轨。该机

器人在发射前附着在一颗小型卫星上，一旦进入轨道，就可以在不使用任何推进剂的情况下跟踪、操纵卫星并使卫星脱离轨道。无推进剂降低了灾难性爆炸的风险，同时减小了尺寸、重量和动力。

关键词：太空垃圾清除，脱轨阻力装置，无推进剂脱轨，SmallSats，CubeSats，碎片避免和清除技术立方体(DART)，小型卫星，立方体卫星

Introduction

As investment in space continues to offer lucrative opportunities for commercial enterprises and government agencies, satellites in space are growing rapidly. For example, in the last seven years there has been a surge in the number of active satellites. In 2015, there were close to 1,400 active satellites. In spring of 2022, the number has grown to almost 5,500. With the advent of Starlink and a variety of other companies entering the new space race, experts from the Government Accountability Office (GAO) estimate that as many as 58,000 satellites will be in orbit by 2030. Most will launch to LEO making it difficult to sustain operations in that altitude range (US GAO, 2022, p. 3).

In an effort to address the space debris problem, this document presents an affordable deorbiting and maneuvering solution for small satellites (SmallSats) that have completed their mission life cycle. The solution is a semi-autonomous system, mounted to a SmallSat prior to launch. The system employs a system of systems approach, utilizing a Deorbit Drag Device (D3), onboard computer system (OCS), independent solar array, electrical power system (EPS), and a stand-alone telemetry, tracking, and command system (TTC). OCS and an artificial intelligence command and control module (C&C) control all of the subsystems. Custom software, built with a low-risk operating system for robots called Robot Operating System 2 (ROS-2) runs on the OCS. D3 is a developmental system now at technology readiness level (TRL) 8. Once complete, the system will function as a bolt-on orbiting robot that will empower SmallSat spacecraft operators with the ability to control and deorbit their spacecraft.

Concept Development

Concept Development is the first step in the systems engineering best practices process. The development of the system begins with identifying the need, exploring the concept to satisfy the need, analyzing the risks of the system, and defining the concept with functions, architecture, and components (Kossiakoff et al., 2020, p. 68).

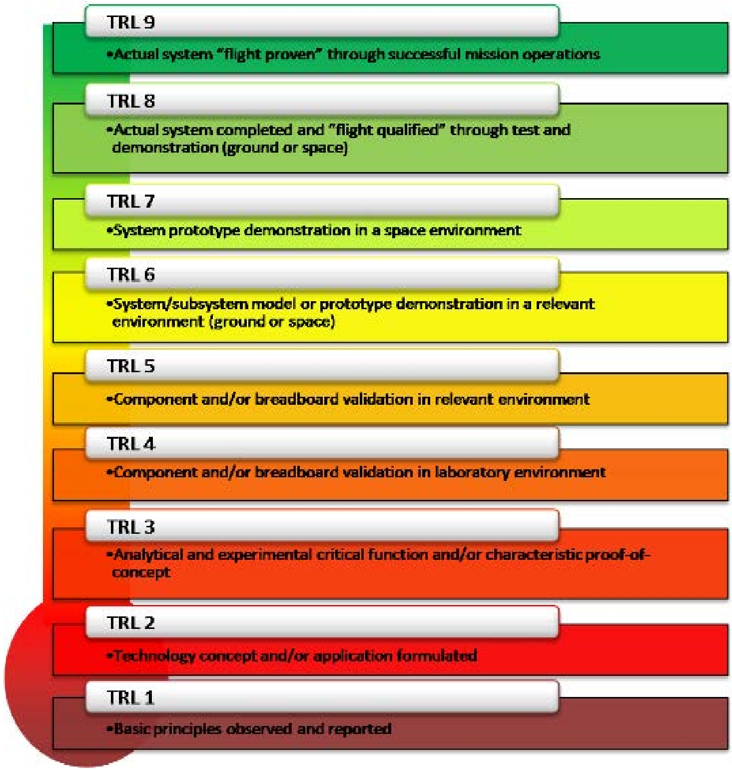

Figure 1. *Technology Readiness Level*

Note. NASA: Technology Readiness Level

Needs Analysis:

With the advent of new U.S. and E.U. government regulations for end-of-life deorbiting of spacecraft, a need has arisen for a cost effective and safe deorbiting system. GAO estimates that almost 60,000 satellites will be in orbit by 2030 and most of these will be in LEO (US GAO, 2022, pp. 3-4). Because the majority of these will be SmallSats, it is clear that operators need a means to track, communicate, maneuver, and deorbit these satellites. Existing methods rely on propellant, reaction wheels, line-of-site ground station communication, and government tracking services such as the Space Surveillance Network (SSN) and ESA SSA Programme (Garcia, 2015). These methods are expensive, dangerous, slow, and problematic. For example, the largest percentage of lost CubeSats occurs shortly after launch due to a loss of communication. They are effectively dead after deployment and never have an opportunity to transmit the root cause of failure. Tracking these satellites can take up to a week in real time. Most CubeSats and many SmallSats do not have the ability to maneuver or perform a controlled deorbit. If equipped with thrusters, they must use heavy propellant, which can lead to high costs, explosions, and more debris (Pike, 2022).

The system described here is an orbiting robot solution for deorbiting, maneuvering, tracking, and communicating with small satellites. SmallSat maneuvering occurs by modulating drag with a subsystem that operates in LEO. The subsystem attaches to the orbiting robot, called a DART Cube (DART). DART is a 1U (standard size & form measuring 10x10x10 centimeters) CubeSat containing tracking, telemetry, and TTC. An EPS with solar panels allows the DART to function independently from the attached small satellite. This feature ensures autonomy and redundancy.

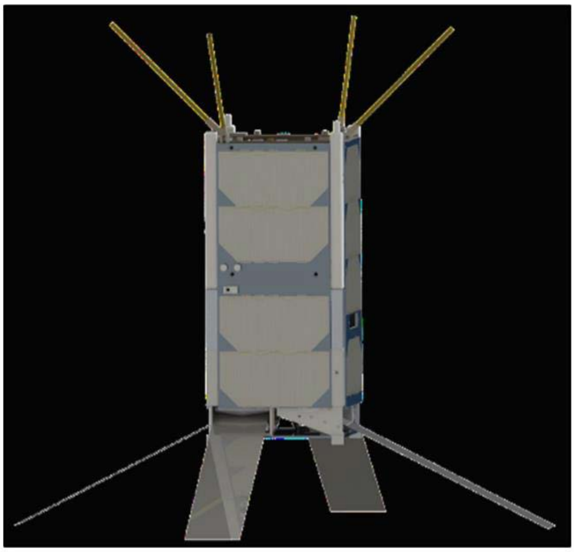

Figure 2. *DART attached to a 2U CubeSat*

Note. Computer-Aided Design (CAD) rendering of DART SmallSat

Concept Exploration:

In this system, the goal is to develop a bolt-on robot called a DART that attaches to a small satellite before launch. Once in LEO, the DART assumes control of the spacecraft. The purpose is to impart tracking, telemetry, command, control, maneuvering, attitude adjustments, and deorbiting operations. Additional applications include staggering constellations and expanding the radar profile of the small satellite. The DART also contains an artificial intelligence command & control (AI C&C) module that communicates with all of the onboard and offboard subsystems. Onboard sensors will provide information to the AI C&C for autonomous maneuvering within a constellation or for external threat monitoring. The DART system does not need explosive propellant and can deorbit and maneuver using drag. The D3 acts as a subsystem for deorbiting and maneuvering a SmallSat up to 180 kg at 700 km altitude (see Figure 3). Using DART, a SmallSat can be deorbited in under five years from up to 600 km (Omar & Bevilacqua, 2019, p. 50).

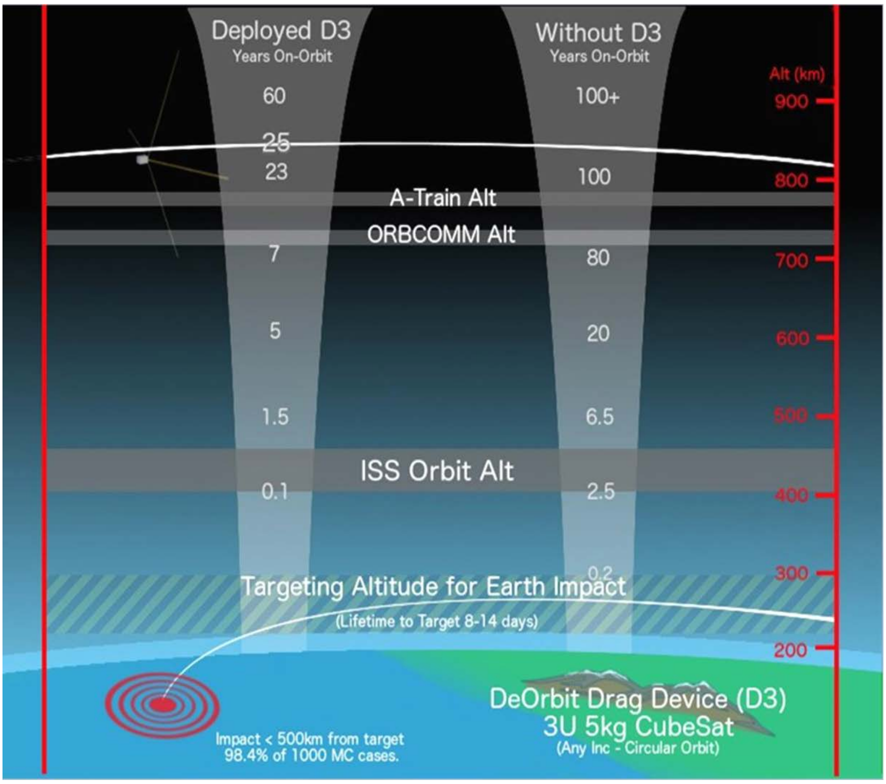

Figure 3. *DART orbital range with D3*

Note. Laurence Fineberg Project: Space Traffic Management Conference

Risk Analysis and Mitigation:

On-orbit failure is always a concern with any spacecraft. The lowest probability events of failure on DART are Global Positioning System (GPS), EPS, OCS, satellite communication system (Satcom), and a D3 boom collapse (see Figure 4). Of these, GPS has the lowest failure rate, followed by the power system, OCS, Satcom, and a D3 boom collapse. The EPS and OCS present serious problems if they go down. In the case of a power failure, a reserve battery system continues powering the deorbiting algorithms, Satcom, and D3 subsystems. If the OCS fails, the D3 can manually respond to commands from Satcom and the ground station. Because the OCS and Satcom are separate subsystems, it is unlikely that both will go down at once (Bratcher, 2010, pp. 14-52).

Other, higher chance risks (21–40%) are integration mistakes, software errors, loosening screws, and a D3 boom deployer failure (Omar & Bevilacqua, 2019, p. 63). A reduction in Integration errors is the goal of quality control during assembly. Software errors may arise, but software patches easily upload from ground computers. There is also a complete manual override available from the ground. The DART goes through qualification testing including a shake test to General Environmental Verification Standards (GEVS) (US NASA, 2022). Any problems with a loosening screw should present themselves in the test. Boom deployers complete 500 repetitions in qualification testing to reduce the chances of deployer failure. If the DART system fails, the SmallSat will not lose capability, meaning that DART adds no extra risk to the mission profile (see Figure 5).

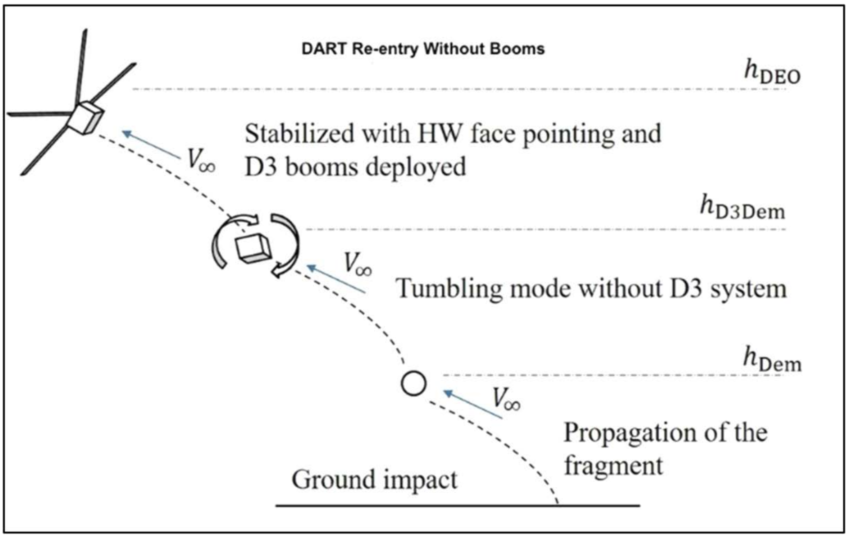

Figure 4. *DART Re-entry without Booms*

Note. D3 controlled SmallSat without booms extended

Impact	1	2	3	4	5
Probability	Negligible	Minor	Moderate	Significant	Severe
(81-100)%	Low Risk	Moderate Risk	High Risk	[illegible]	[illegible]
(61-80)%	Minimum Risk	Low Risk	Moderate Risk	High Risk	[illegible]
(41-60)%	Minimum Risk	Low Risk	Moderate Risk	Boom Deployer Malfunctions	High Risk
(21-40)%	Minimum Risk	Integration	Software Error	Screws Loosen	High Risk
(1-20)%	Minimum Risk	GPS Fails	EPS Fails	Onboard Computer or Satcom Fails	Booms Collapse

Figure 5. *Risk Analysis & Mitigation*

Note. Orbotic Systems: Risk analysis breakdown for DART

To minimize on-orbit failures, DART uses commercial off-the-shelf (COTS) TRL9 components (space legacy) whenever possible. Running tested and validated algorithms on commercial flight heritage computer hardware is common practice and low risk. The most probable on-orbit failures are likely to be in-house components, namely the D3 device and flight software. Mitigating these high-risk activities involves extensive modeling analysis, qualification testing, and functional testing (Guglielmo, Omar & Bevilacqua, 2018, p. 137). See Figure 6 for AI C&C software structure.

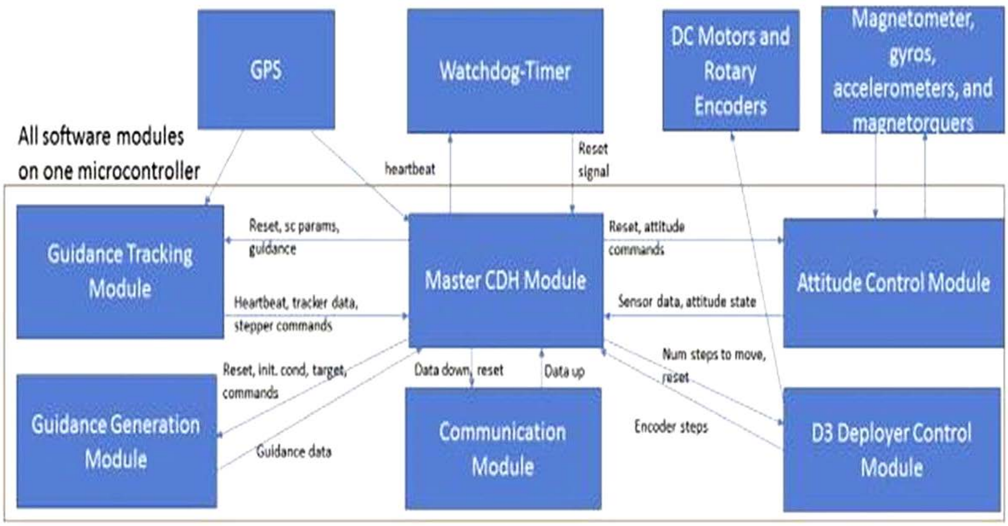

Figure 6. *Software Block Diagram for AI C&C*

Note. Guglielmo, Omar & Bevilacqua: AI C&C software diagram for DART

Concept Definition:

Performance requirements analysis compared the DART requirements with the needs validation data, as shown in Figure 7. It was determined that the requirements match the need which led to a functional analysis and formulation.

A functional block diagram outlines the operation of the functions and the subsystems, as shown in Figure 8. The yellow ovals represent environmental effects external to the DART system. The green rectangles symbolize the subsystems or actions performed by the DART. The orange rectangle displays the subsystems or actions that require electricity to perform.

Trade-off analysis of DART/D3, DART/thruster, and no DART in a weighted sum integration table verified that the D3 DART was the best selection match for the needs analysis (see Figure 9).

Concept validation of materials specifications implemented a series of modeling simulations. Materials tests identified that materials shall meet NASA-STD-6016, Standard Materials and Processes Requirements for Spacecraft and NASA Reference Pub. 1124, Outgassing Data for Selected Spacecraft Materials (US NASA, 2020, 23, 70). Thermal analysis simulations for orbits of interest over an entire solar year identified any DART surface areas of concern. Attitude dynamics simulations of the D3 with boom angles of 20 degrees demonstrated aerodynamic stability up to 700 km altitude. What's more, booms can adjust in orbit to create a moment-of-inertia axis that will align with the nadir vector due to the gravity gradient torques (Guglielmo, Omar & Bevilacqua, 2018, pp. 140-141).

Measures of Effectiveness (MOEs)	Min/Max	Target
SmallSat Weight	Max	180 kg
SmallSat Size (DART³ extra)	Max	12U
SmallSat Size (DART³ extra)	Min	1U
Altitude Ceiling	Min	600 km
Deorbit Time (Max Altitude)	Max	5 years
Re-entry Destination Error	Max	500 km
Tracking Updates (GPS)	Max	1 month
Tracking Updates (GPS)	Min	1 minute
Communication Cycle	Max	1 month
Communication Cycle	Min	1 minute
SmallSat Differentiation	Min	6 meters

Figure 7. *Needs Validation Data*

Note. DART Needs Validation Data Chart

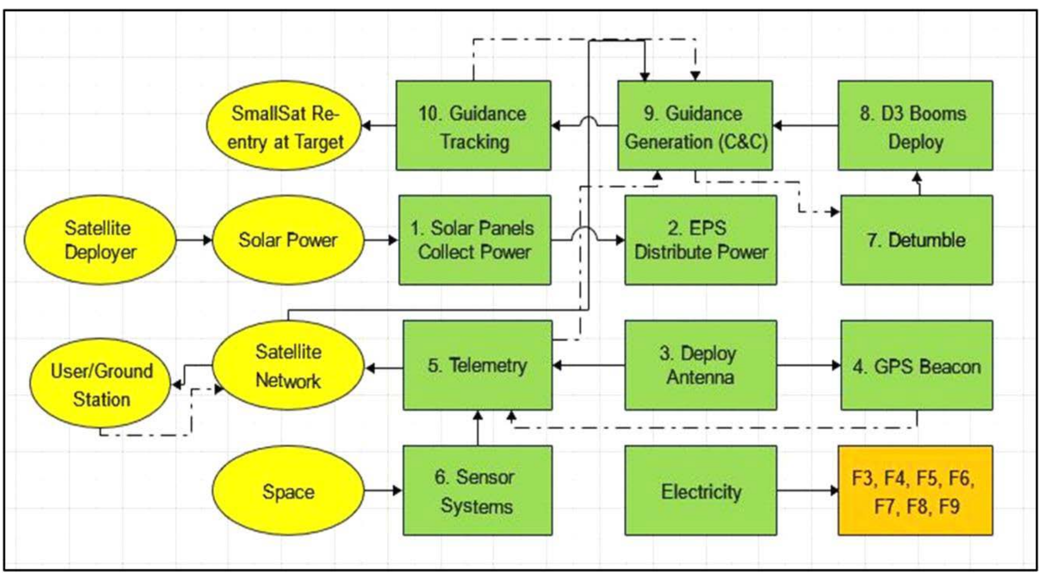

Figure 8. *Functional Block Diagram*

Note. Functional Block Diagram of DART system

Name	Analysis	Proposal	Targets	Outlook
DART³	Subjective Value Method of DART³ "Protype"	Three Concepts with Value (1-4)	Performance, Risk, Cost, Schedule	Best Concept

Selection Criteria	D3 - DART³			Thruster - DART³		No DART³	
	Weight	Value	Score	Value	Score	Value	Score
Performance	**40**	3	1.2	4	1.6	1	0.4
Risk	**30**	2	0.6	1	0.3	3	0.9
Cost	**20**	3	0.6	1	0.2	4	0.8
Schedule	**10**	3	0.3	2	0.2	4	0.4
TOTAL	**100**	**11**	**2.7**	**8**	**2.3**	**13**	**2.5**

Figure 9. *Trade-off Analysis*

Note. Trade-off Analysis of D3-DART, Thruster-DART, and No DART

The AI C&C module uses COTS systems and parts. Radiation-hardened electronic components have flight heritage. Software used is readily available and includes C++, Python, and ROS-2.

Engineering Development

Engineering development has three phases. Advanced Development consists of risk management, subsystem definition, and component specifications. Engineering Design includes component engineering, component testing, and specialty engineering. Integration and Evaluation consists of system integration, system tests, and operational evaluation.

Advanced Development Phase:

Significant unknowns exist at this phase. While the Concept Development phase has laid a foundation for the system, it is necessary to define unknown variables in the engineering phase. In this section, the emphasis is on identifying and reducing the development risks while developing specifications (Kossiakoff et al., 2020, pp. 70-71). The first step in reducing risk is validating the concept through requirements analysis.

Requirements Analysis – In the concept development phase, several functional requirements identified with their supporting subsystems take place. Each of the functions group into a subsystem that comprise the DART system. Every subsystem performs part of a mission activity for the small satellites. Except for propulsion, all subsystems accommodate components that are readily available as COTS items. In the case of the D3, there are some components that need custom development. The D3 is an independent subsystem that will satisfy the role of the propulsion subsystem. As it stands today, the D3 has a TRL of 8. All other subsystem components have extensive flight heritage, making the D3 subsystem the primary risk for developing the DART system.

Functional Analysis and Design – Besides the D3 and in-house software, the subsystem components have flown in space on different missions. Despite that fact, the DART architecture is new and may present unknown issues. The key factors affecting functionality are C&C, EPS, and Satcom. Critical concerns rest with failover and redundancy. While communications through ground stations can substitute for the OCS, neither one can function without electrical power. An independent backup power system for these subsystems, and the D3 solves this problem. At the very least, it allows DART to perform an end of mission deorbit if all other SmallSat systems fail (Omar & Bevilacqua, 2019, pp. 60-63).

The D3 operates as an independent system, so no further design modifications need to take place with this subsystem. D3 passed tests involving simulation testing, mathematical modeling, and extensive GEVS CubeSat laboratory testing (Guglielmo, Omar & Bevilacqua, 2018, pp. 131-142).

Prototype Development – One risk mitigation technique is to build a prototype. Developers use prototypes to identify and mange risks. Specifically, a prototype can help the engineers identify, which components and subsystems demand additional development and testing (Kossiakoff et al., 2020, p. 367). Complex systems will benefit from prototypes in many instances, as long as the benefits do not cause any significant cost or time delays.

Because the DART system operates in an extreme environment (LEO), it can certainly benefit from a protype. Specific interest pertains to the D3, D3 booms, D3 boom deployers, and flight performance versus simulations and computer modeling. The prototype benefits from additional verification of the Satcom, GPS, TTC, OCS, C&C, EPS, and custom software. DART prototype analysis performed in the concept development phase indicates cost and schedule feasibility for the system. The primary extra costs for the prototype are the qualification testing and the software development.

Development Testing – Not to be confused with "developmental testing" and "operational testing," development testing will include a series of tests in controlled environments on the components and subsystems (Kossiakoff et al., 2020, p. 376). The tests will conform to a test engineering management plan (TEMP) and use existing CubeSat test facilities that will aid in keeping the costs down. Fortunately, a series of test plans already exist for testing CubeSats and SmallSats, easing the burden of the test process.

Testing for the D3 and the DART structural components will include baseline vibration and sine vibration testing, baseline shock testing, baseline thermal vacuum cycle (TVAC) and functional testing, and post environmental functional testing. Tests will be to NASA GEVS standards where appropriate. Deliverables at this point are a Vibration Test Report, Shock Test Report, Thermal Vacuum Test Report, Functional Test As-Run Procedures (Guglielmo, Omar & Bevilacqua, 2018, pp. 131-142). Satcom tests using satellite network simulations provided by the constellation network provider (e.g., Iridium, Globalstar, etc.) verify the functionality of the Communications subsystem.

The D3 testing included simulations that suggest a "dart" configuration of booms provides stabilization along the z-axis in alignment with the velocity vector. The trajectory targeting algorithm testing used a Monte Carlo simulation with random models of natural orbital conditions, including drag uncertainty and GS sensor noise. After running one thousand simulations, all cases demonstrated that guidance generated by the D3 duplicated realistic natural orbital trajectories (Carna et al., 2019, pp. 427-433).

Final testing on the C&C software allows for a conventional software laboratory setting. ROS-2 is designed specifically to build robot applications and will frame the software.

Engineering Design – This phase serves several purposes including the identification of any unproved components and "unknown unknowns" that have escaped notice in the advanced development phase. Components and parts should function and integrate as intended to avoid design doubts or concerns. The component integration produces a system that meets the operational requirements. Established internal or external interfaces and components integrate as expected within the allotted budget (Kossiakoff et al., 2020, 449).

Requirements Analysis – External system interfaces, user interfaces, and environmental interfaces require special attention (Kossiakoff et al., 2020, p. 481). The DART has interfaces that fall in all three of these categories. One of the benefits of the DART to the user on the ground is the ability to interact with it real-time by using an existing communications constellation. This simplifies the approach that the SmallSat operator must take, because they can run proprietary software on the ground and use it to directly interact with the DART for satellite control. Consequently, the DART is much more useful than only as a deorbiting mechanism. Real-time TTR with GPS is an additional benefit and acts as a user interface. Many SmallSats, particularly CubeSats become lost because of the orientation of the onboard antenna with a ground station antenna. DART solves that problem with a prefabricated satellite transceiver and GPS tracking device. The combination allows users to extend DART applications in creative ways. The ROS-2 operating system used for DART can integrate with many software languages. More software expands the range of use of the OCS for the operator's proprietary purposes.

The DART will interface with the external GPS, Satellite constellation, LEO, solar radiation, launch vehicle shock and vibration, deployer mechanism, ground users, and Earth's atmosphere. The original concept development includes these interface considerations.

Functional Analysis and Design – The DART design uses a modular approach called Modular Open System Architecture (MOSA). Important goals of this approach include modularity in regard to interactions between the system components and environment (Kossiakoff et al., 2020, p. 456). Software design, architecture, and interfaces must also accommodate modularity. MOSA offers redundancy, testing, and upgrading simplicity for the DART system.

The DART carefully isolates subsystems and their components by function. There is very little dependence on one subsystem to another. The only exception to this is the OCS. The AI C&C module resides on the OCS, so some of the functions in different subsystems need regulation by the OCS. However, there is a redundancy system in place that uses the Communications subsystem as a back-up to take control of the D3 and thereby guidance, navigation, and control (GN&C) if the OCS fails. More integration modularity includes an independent back-up battery system to power the D3, a deorbit microcontroller, and the communications transceiver. Because the DART can operate most of the time on little power, it is possible to conserve power while the SmallSat performs mission duties. If the mission includes DART functionality, ground control can override or control the SmallSat by communicating with the DART. In this manner, ground control can also provide back-up control through the Communications subsystem if the OCS goes down (see Figure 10).

Component and Software Design – Integration of the functional requirements using engineered software and hardware components with testable interfaces is the objective of component design. The focus is on non-existent components needed for the subsystems and a prototype (Kossiakoff et al., 2020, p. 460).

The DART architecture emphasizes COTS components and software. Owing to the nature of the device and barring any objections in the preliminary design review (PDR), the architecture leans toward flight heritage components whenever necessary. The OCS will require new software built with ROS-2 and tested on the ground with all connected subsystems. An area of concern is the efficient integration of the subsystem components. This issue requires intensive inspection in the critical design review (CDR). Integration engineers must bear in mind that different components will integrate for the first time in DART. The software in the OCS AI C&C module will coordinate with several subsystems at once. For this reason, a software test must take place before and after system integration.

Design Validation and Configuration Items – Validation of the component implementation takes place in design validation. This deals with the physical building blocks of the subsystems. Test planning should begin early, to allow enough time to procure the necessary

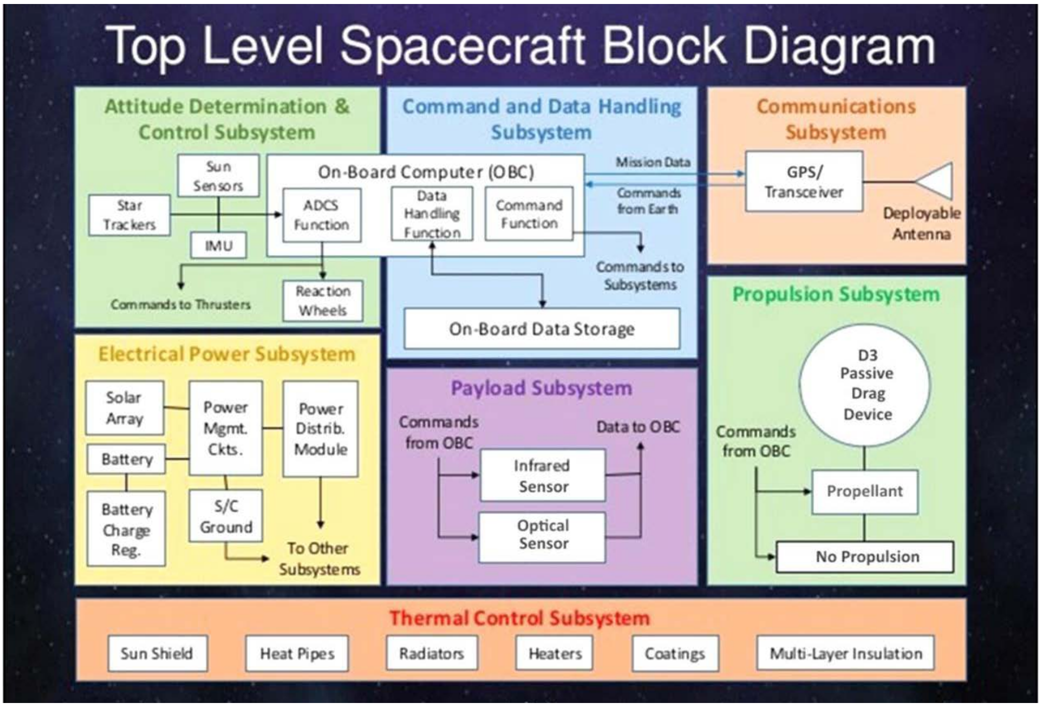

Figure 10. *Subsystem Block Diagram*

Note. Block diagram of DART and inclusive subsystems

test equipment and facilities (Kossiakoff et al., pp. 473, 482). The testing conducted at this point is different from the previous development testing phase. In this case, the individual components test separately and then again as integrated. With DART, each finished subsystem will test independently before a linked integration with other subsystems begins. The plan will follow a sequential buildout with a separate test conducted for each subsystem interface. Finally, all of the subsystems functioning together must pass a performance test. An evaluation of reliability data and statistics, collected from all test procedures, ensues for all test validations. Final testing will include failover and redundancy tests for all backup power systems individually and collectively. The baselines for a configuration will begin in the concept exploration and used throughout the design validation phase (Kossiakoff et al., 2020, p. 478).

Integration and Evaluation – This is the point in the system lifecycle where all the components assemble into subsystems and integrate to operate together in a completed system. The goal is to demonstrate that the system works and meets the original operational requirements. A designated integration engineer will be selected to lead the integration process. The systems engineer will need to convey functionality of each subsystem to the integration engineer. The subsystems will be mounted in the DART Cube form factor using custom prefabricated mounting plates and shelves. These can be pre-ordered from a machine shop by using CAD files. Before the subsystem components are installed, the integration engineer should test the connected subsystems whenever possible. Any questionable test results should be noted and delivered to the systems engineer immediately (Kossiakoff et al., 2020, p. 485).

System Integration – Because of the many components that form the subsystems in a complex system, it is necessary to assemble and operate the whole system to reveal incompatibility problems. The DART is a semi-autonomous, 1U cube that mounts onto a SmallSat to maneuver and deorbit the spacecraft. Additional functionality depends on the operator. Consequently, integration to specifications is possible on the ground, but true integration capability is unknown until the completion of an operational performance test.

System Test – The DART comes equipped with onboard sensor systems analyzed by the AI C&C and the OBC. If the AI identifies a collision threat, it will make that information available to the operator. At this point, a manual decision or an autonomous decision to maneuver the SmallSat with the D3 occurs. Avoidance maneuver planning determines the procedure in advance. Meanwhile, the AI database is storing sensor pattern data that indicates the likelihood of a threat. This data downloads to a ground station computer for future evaluation or refinement by the operator's proprietary mission planners. In addition to collision threats, maneuvers can be pre-programmed for pre-determined orbital trajectories or interacting with constellations.

Operational Evaluation – An operational test will demonstrate DART subsystem integration and how the subsystems should operate collectively. Once there is operational confirmation, it is reasonable to expect timing and trajectory modifications introduced by the user and performed by the DART. Autonomous maneuvers fall within this category as well as mission specific ground command maneuvers.

Operational testing is possible from the ground. However, there is no way to test that the fully integrated subsystems work properly until the completion of a DART operation in LEO. Ideally, any in-situ testing uses a ground station, data links, and a satellite communications constellation. Testing also requires an operating DART, attached to a SmallSat, orbiting in LEO.

Schedule and Budget – The life cycle development must include a schedule for completing the DART. In order to stay on schedule, a budget is required in advance of the start date. The DART schedule is summarized in Figure 11. Each deliverable corresponds to the engineering development phases.

The Budget for the DART is listed in Figure 12 below. The first column is an estimate of the costs for the first prototype. The second column is an estimate for the production model. The asterisk represents items that may vary depending on the mission profile.

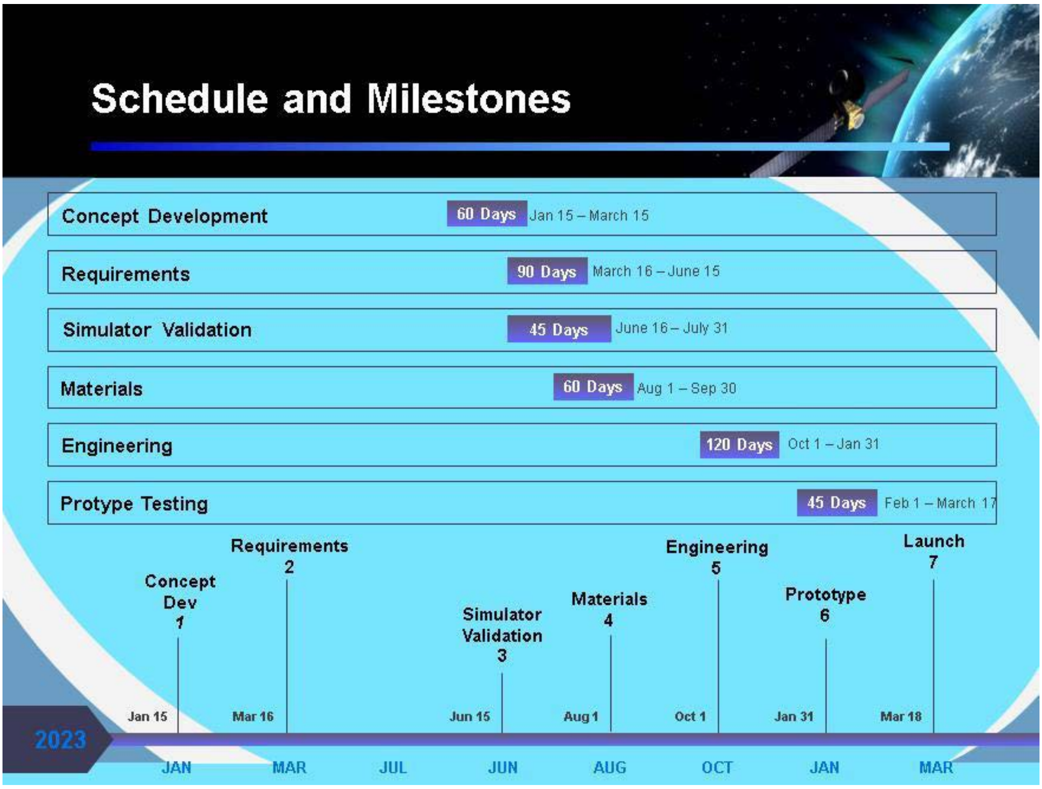

Figure 11. *DART Prototype Schedule*

Note. Schedule begins January 15, 2023

Expense	DART³ (Prototype)	DART³ (Production)
COTS*	$38,300*	$38,000*
Satcom*	$1,200/yr*	$1,200/yr*
Software*	$40,000*	$4,000*
Sensors*	$14,500*	$14,500*
D3 (ADCS*)	$9,000 ($37,400*)	$9,000 ($37,400*)
Labor	$32,000	$32,000
Testing	$25,000	$5,000
Total Cost	**$160,000**	**$103,700**

Figure 12. *DART Budget*

Note. Asterisk items can vary per mission

Post-Development

All activities after the lifecycle development requiring assistance from systems engineering take place here. Unanticipated problems need an immediate solution by trained personnel. Other activities are system updates that accommodate advances in technology. Post-development begins after operational testing and evaluation. At this point, a fully functional system for production and operation exists (Kossiakoff et al., 2020, p. 66). Post development consists of two primary phases. They are the production phase and the operation and support phase.

Production – The output of this phase is the replication of the engineered system, formulated in the system development life cycle. The efficiency of production is dependent on the procurement of duplicate hardware and software used to build the system in the operational evaluation. Production requires the tooling, equipment, and personnel necessary to duplicate the system in the production facility (Kossiakoff et al., 2020, p. 539).

Procurement of Material – The components for the subsystems come from a variety of vendors. In the case of the DART, vendor procurement involves the least number of vendors as possible. This limits the number of service personnel and lowers the costs through bulk purchases. Digi-Key is the vendor for individual parts and components, while pre-fab subsystem components come from EnduroSat. As a large supplier of SmallSat equipment with established flight heritage, EnduroSat is in a position to provide equipment, service, and upgrades on demand as production increases. Because the D3 is not mass manufactured, it will need additional pre-fabrication of parts and COTS components. A bill of materials (BOM) from the D3 inventors and patent holders lists a variety of components that are COTS and available from Digi-Key and other easily accessible suppliers. Specialty pre-fab parts come from CAD designs, and a company with aerospace fabrication experience such as Xometry. Software written in-house uses ROS-2, which is an established global standard.

Production Operations – Planning, designing, and operating the production of the DART system takes place in this phase. Production operations include the acquisition of components, functional test equipment, component manufacturing facilities, software testers, pre-fabrication facilities, configuration management, information system with database protocols, production staff, production budget, inventory planning, and testing staff (Kossiakoff et al., 2020, p. 558).

Operations and Support – In theory, the systems engineering tasks are complete. However, there are usually technical tasks associated with continuing installation, testing, and component replacement. Random user error or equipment failures will occur. In these cases, systems engineering practices apply to the operators, maintenance staff, or outside engineering services (Kossiakoff et al., 2020, p. 561).

Installation and Test – The system installation requires mounting the DART to a variety of different SmallSats with different mission profiles, size, and weight. A custom designed mounting plate facilitates attachment. The DART can easily attach with a 1U mounting plate at the customer location.

The autonomous nature of the DART simplifies the installation. Communication with the DART OCS can take place prior to or after installation. The DART will respond to simple commands generated by the user's proprietary software system. Communication takes place between the ground station and the DART by way of the orbiting communications satellite constellation. Once there is contact between the ground station computer and the DART, the various DART subsystems lend themselves to indirect testing.

In-Service Support – The DART software system has self-healing diagnostics to analyze each subsystem and confirm operational capabilities. The software will also alert the user to any functionality issues and identify back-up solutions. The functionality performs automatically between the AI C&C module, the OCS, and the user. Because of this built-in capability, each unit has remote testing and support capability. Once in orbit, the OCS and communication system will be the only means available to service the DART, allowing the user to monitor health and provide back-up support. Service personnel in the production facility will be on hand to test each DART and address any hardware issues before stocking and delivery. Updates to the software can easily upload from the ground by support personnel.

Major System Upgrades: Modernization – The DART has modernization and system upgrade conveniences. There are three areas that are likely to need modernization. One is the OCS, two is the AI C&C module, and three is the D3. The OCS hardware can swap out with modern replacements and still run the ROS-2 software. Software updates take place at the time of the new OCS installation or from the ground station to orbit. The D3 operates as an independent subsystem and connects via an OCS sister board that can easily interface with a new D3 model or another piece of propulsion hardware.

Disposal – Once in orbit, the DART has an existing deorbit plan designed for the mission after the mission life cycle is complete. The deorbit must occur in five years or less after the SmallSat ceases to function or the SmallSat mission ends. If the DART system needs updating or replacement with a better deorbiting solution, retirement of the DART is possible in stages or all at once. Threat analysis data collected by the orbiting DART lends itself to storage in a software database. The data has value for research or refinements in a new system.

Conclusion

This paper presented the life cycle of the DART Cube system. The DART integrates a set of common SmallSat subsystems with an OCS and AI C&C module. DART introduces a unique subsystem to control and deorbit a SmallSat called a D3. An OCS coupled with the AI C&C module controls the DART and allows it to maneuver, lower, and deorbit a SmallSat. DART has space situational awareness (SSA) by using two onboard sensor systems, which allow it to perform a collision avoidance maneuver (CAM). The convenient design criteria for mounting, testing, controlling, and upgrading make the DART easy to support.

The purpose of introducing the system is to offer greater satellite control, communications, tracking, and deorbit. It also provides a space debris mitigation solution for dead satellites. The DART can deorbit within the new five-year FCC requirement for defunct spacecraft. The addition of the DART to SmallSat operations will not only ensure real-time tracking, orientation, and trajectory control, but also expand mission profiles and lower costs for operators. Precise targeting of re-entry trajectories will help SmallSat operators use more durable materials for their satellites by deorbiting over non-populated areas. The DART promises to be a cost-effective space debris mitigation technology with vast benefits.

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