A Systems Engineering Approach to Design, Fabrication, and Characterization of a Modern Spacecraft to Study Impact Patterns of Space Debris

Ann Dietrich, Sheldon Clark, Mark Werremeyer, and Dr. Norman Fitz-Coy

College of Engineering, University of Florida

The NASA Standard Breakup model, which predicts orbital debris fragments from on-orbit collisions, was discovered to be out of date when it inaccurately predicted the number of fragments in the Cosmos-Iridium collision that occurred in 2009. To update the model, a representative modern spacecraft must be fabricated and subjected to a hyper-velocity impact to generate debris fragments, which are then characterized and used in the model. This effort addresses: (i) definition of a representative modern satellite; (ii) development of the detailed spacecraft design; (iii) fabrication, assembly, and testing; and (iv) cost constraints and documentation of the project.

NOMENCLATURE

ADCS	= attitude determination and control system
CAD	= computer aided design
CDH	= command and data handling
CIC	= coverglass-interconnect-cell
COTS	= commercial off-the-shelf
ESA	= European Space Agency
LEO	= low Earth orbit
Li-ion	= lithium-ion
NASA	= National Aeronautics and Space Administration
NiCd	= nickel cadmium
NiH_2	= nickel hydrogen
SME	= subject matter expert

INTRODUCTION

The number of man-made objects in Earth orbit has been consistently increasing, and roughly 6% of the 15,000 traceable objects of larger than 10 cm are active satellites.[1] The remaining objects are considered orbital debris and include retired satellites, upper rocket stages, and the remains from on-orbit collisions. In 2009, the accidental collision between an active Iridium satellite and a retired Cosmos satellite highlighted the need to study on-orbit collisions of modern satellites. As collisions occur, more space debris will be produced, which increases the likelihood of collisions; this is also known as the "Kessler Syndrome."[2] Thus, even if no more spacecraft are launched, the debris environment will continue to escalate, with heightened activity in Low Earth Orbit (LEO).[3] The NASA Standard Breakup Model approximates the fragments produced from an on-orbit collision. However, the current model is based on a 1992 impact test centered on a Navy Transit satellite (~40 cm, 35 kg) fabricated in the 1960s. When this model was applied to the Iridium-Cosmos collision, it performed well for the Cosmos-2251 fragments, but underestimated the number of fragments produced from the Iridium-33 satellite.[4] Satellites developed today incorporate new materials and technologies, and therefore there is a need to perform new impact tests with a satellite that incorporates modern materials and construction practices.

The overall goal of the project was to design and construct a "next-generation" non-operational satellite, named DebriSat, that is representative of current and future low earth orbit (LEO) satellites. This design incorporated new materials such as multi-layer insulation, composite materials, and CIC solar panels. The target mass of DebriSat is 50 kg, but its design represents all mass ranges of LEO satellites. DebriSat will undergo a hyper-velocity impact test at Arnold Air Force Base, and its fragments will be studied to provide a better understanding of the 2009 Iridium fragments as well as future satellite breakups.

PURPOSE

The purpose of this specific project was to gain a better understanding of the satellite design process and to study the design and fabrication of DebriSat from a systems engineering perspective. In particular, this project studied the characterization, design, and fabrication processes undertaken in the development of DebriSat, and addressed the following topics:

(1) Definition of a representative modern LEO satellite
(2) Development of the satellite subsystems
(3) Fabrication, assembly, and testing of DebriSat
(4) Cost constraints and documentation process

Definition of a Representative Modern LEO Satellite

To define a "modern LEO satellite" properly, publically available data on current satellites and their subsystems was utilized to identify and characterize emerging trends and traits in recently launched LEO satellites. Using a database of 467 satellites tracked by the Union of Concerned Scientists, a subset of 50 satellites was formed. These 50 satellites were chosen based on their mass, to represent a similar mass distribution as the larger database, and their launch date, to focus on the most recent missions. Each satellite was classified by their mass into six categories: 1-10 kg, 10-100 kg, 100-500 kg, 500-1000 kg, 1000-2000 kg, and 2000-5000 kg. Next, research was performed to characterize each satellite subsystem and the satellite's history. The categories included attitude determination and control (ADCS), command and data handling (CDH), electrical power systems (EPS), communications, payload, propulsion, structure, country of origin, and launch date. The telemetry, tracking, and command (TT&C) subsystem was included in the design of DebriSat, but was not included in the representative satellite study. The components researched in each category were translated into common terminology, and component trends were developed between each of the mass categories. Figures 1 through 4 show some of the component trends developed. Figure 1 represents the percent usage of ADCS actuators by mass, and reveals that magnetorquers and reaction wheels are the most readily used actuators in modern LEO satellites. Figure 2 shows that the most common frequency bands used on modern satellites are S-bands, X-bands, and UHF-bands.

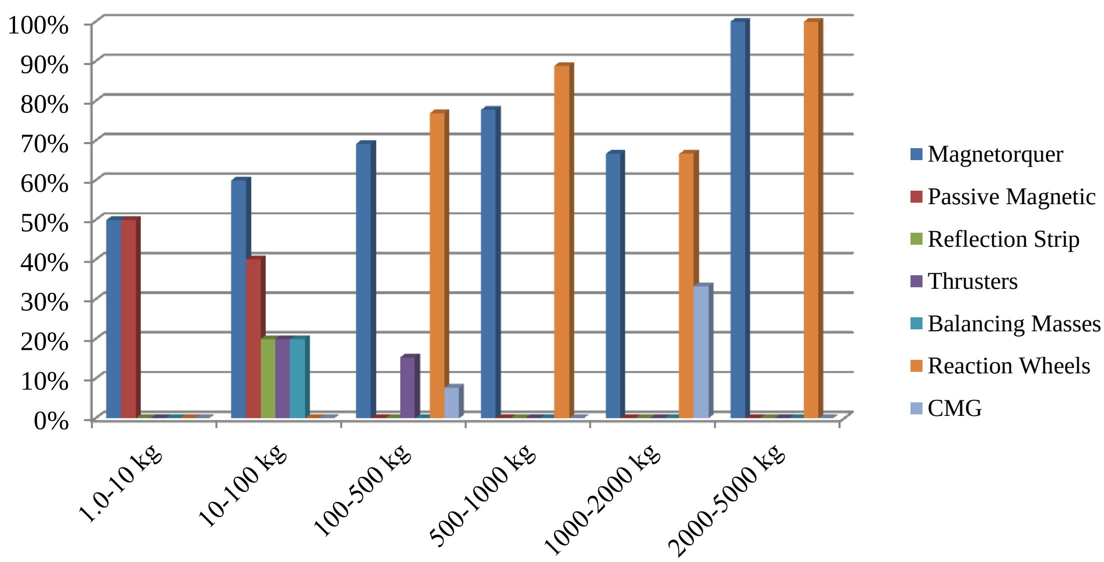

Figure 1. ADCS Actuator Usage by Mass. Representation of the actuators used in typical LEO attitude determination and control systems. Magnetorquers and reaction wheels are the most prevalent.

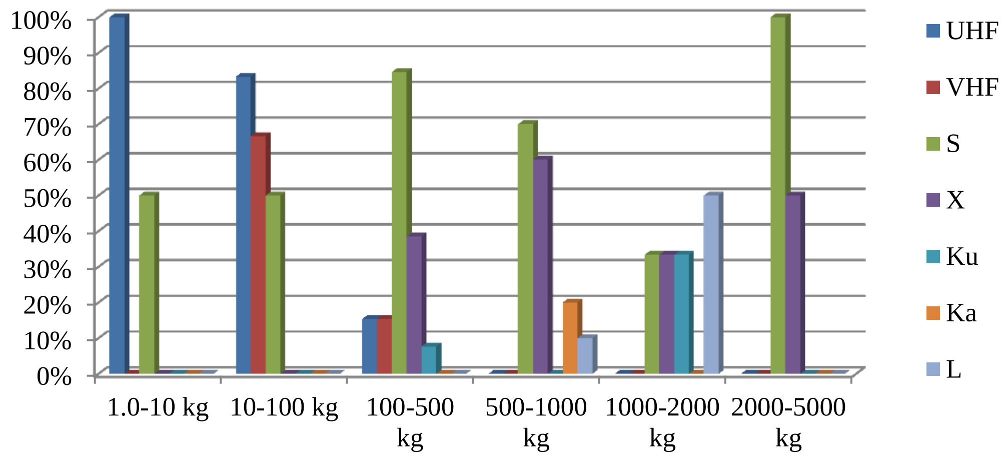

Figure 2. Frequency Bands Percent Use by Mass. Representation of communication frequency bands usage, broken down by mass, for a typical LEO satellite. The most common bands are S-bands, X-bands, and UHF-bands.

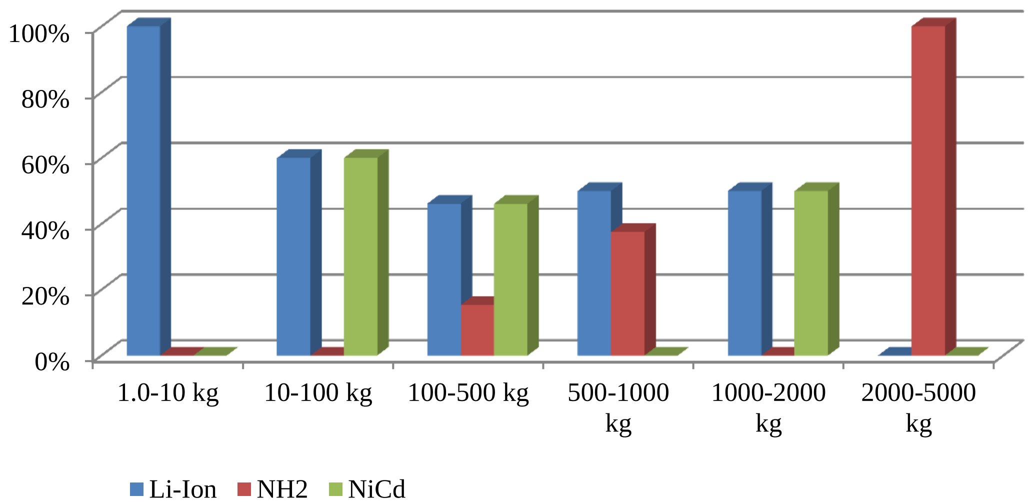

Figure 3. Battery Type Percent Usage by Mass. Battery types found in typical LEO satellites. Li-Ion batteries are seen in smaller satellites and NiCd and NH2 are seen in larger satellites.

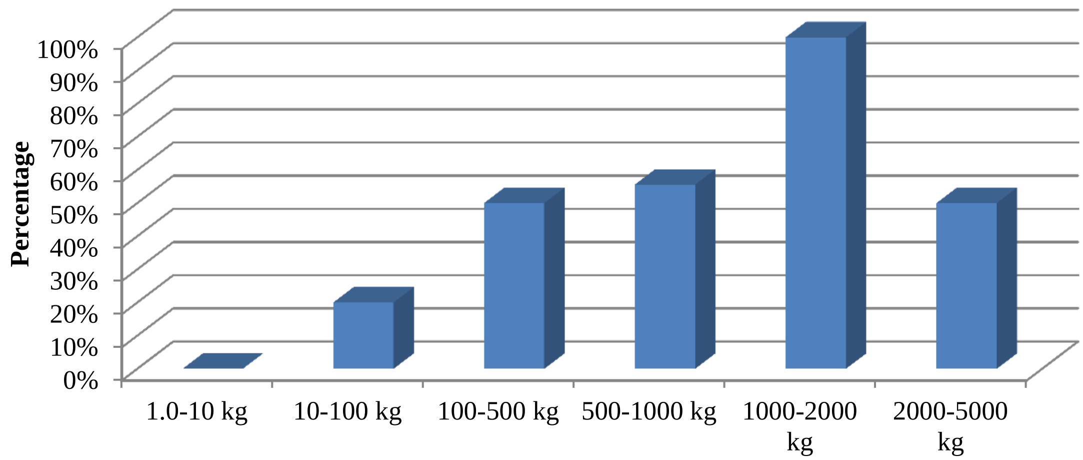

Figure 4. Percent Usage of a Propulsion System by Mass. Percent of satellites with a propulsion system in each mass category. Most larger satellites include propulsion systems.

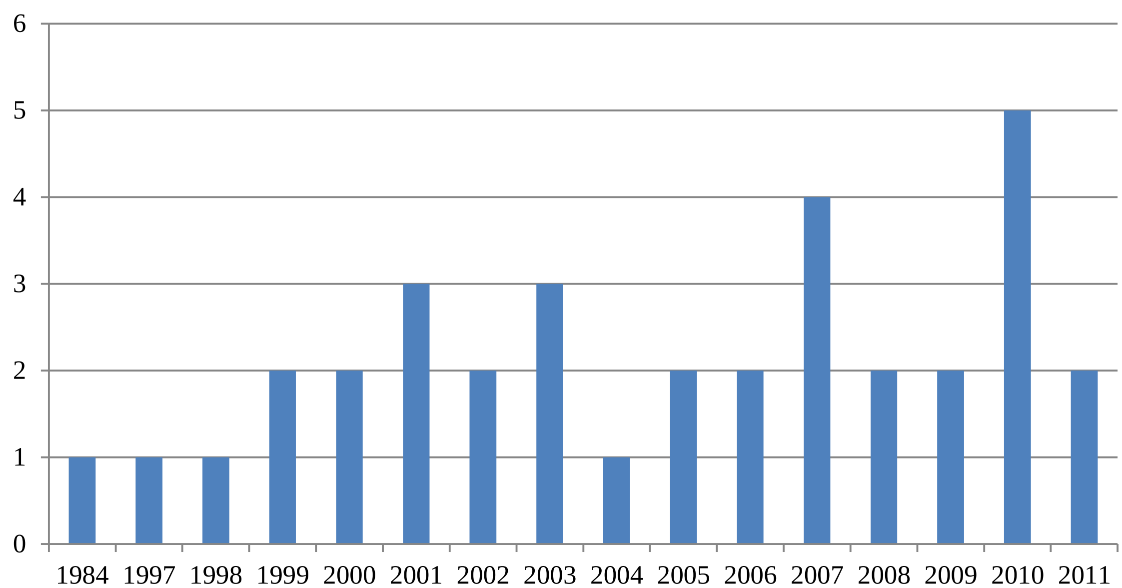

Figure 5. Launch Dates of Selected Satellites in Database. Distribution of launch dates of satellites in the database to support the claim of a representative modern LEO satellite.

As shown in Figure 3, Li-Ion batteries are used in lower mass LEO satellites, while NiCd and NH2 batteries are used in larger satellites. The design process for the larger satellites most likely began 10-20 years ago, while development of the smaller satellites most likely began 5-10 years ago, when more information was available on Li-Ion technology. Therefore, an increase in Li-Ion batteries in smaller satellites implies an emerging trend in Li-Ion batteries in modern day satellites. One can infer that Li-Ion batteries are being tested in smaller satellites, and are steadily increasing in use in larger satellites.

Figure 4 illustrates the percent usage of propulsion systems by mass. As shown, satellites larger than 50 kg usually include a propulsion system. However, to create a representative satellite of all mass ranges, a propulsion system was included in DebriSat's design. Figure 5 represents the launch dates of the satellites chosen, and supports the claim that a modern subsystem database was developed.

Various limitations arose in the development of this subsystem database. One limitation is the sample size of 50 satellites, and another is the availability of information in the public domain. In addition, most of the satellites' country of origin was the United States, with the European Space Agency (ESA) producing the second highest. There was little to no information on satellites originating from China or Russia, which forced the exclusion of these missions. A larger sample size, access to satellites in large constellations, such as Iridum, that are not found in the public domain, and information on foreign satellites would improve the validity of this database.

The characterization of a modern LEO satellite can most readily be classified as Phase B: Preliminary Definition. The task was to design a representative LEO satellite, but first the definition of a representative LEO satellite had to be determined. This step provided a starting point in defining the components and subsystems to be included in DebriSat.

DEVELOPMENT OF DEBRISAT SUBSYSTEMS

Each subsystem was assigned to a team member to be further researched and designed, and the component trends (Figures 1-4) drove the basics of each design. In addition, historical mass fractions for each satellite subsystem were provided by the Aerospace Corporation and provided a target mass for each subsystem to match the target overall mass of 50 kg. Utilizing modern materials, representative components, and the subsystem mass fractions were emphasized in the design.

Although the target mass of DebriSat is 50 kg, the design aims to represent all LEO satellites ranging from 1-5000 kg. Therefore, for DebriSat to represent a modern LEO satellite, some components were included in the design that would be redundant in operational satellites. For example, several different frequency band antennas and several different sensors for the ADCS were included in the design. The components included in the design were determined from the subsystem database, and some were scaled to match the historical mass fractions of each subsystem.

Through bi-weekly telecoms with NASA Orbital Debris Program Office, the Aerospace Corporation, and the Air Force Space and Missiles Systems Center, multiple subject matter experts (SME) were polled throughout the development of this design. Consulting with these SMEs helped to determine if each subsystem was truly representative of modern satellite subsystems and construction practices.

Since DebriSat will not be operational, several components were imitated to reduce costs. These components were designed from drawings and models found from commercial off-the-shelf (COTS) vendors in the public domain. The focus of each emulated component was matching the correct mass, materials, and performance specifications one would expect from an operational component. In addition, alternatives to a typical subsystem were explored to reduce costs. For example, the propulsion system design is centered on a nitrous oxide kit that includes very similar components, materials, valves, and performance measures to a typical satellite propulsion system.

Developing a final design based on the component trends and SMEs can be classified as the Detailed Design phase. Once the purpose and definition of the design is established, the design was refined to the point that it can be fabricated and assembled.

FABRICATION, ASSEMBLY AND TESTING

Virtual modeling and integration of each component is currently underway. Figure 6 shows a preliminary model of the exterior structure of DebriSat. Each component, including acquired and manufactured components, is being modeled in SolidWorks and will be virtually packaged in an assembly. The placement of each subsystem depends on its subsequent components. For example, propulsion thrusters must be distributed strategically throughout the structure to provide proper mobility as would be seen in an active satellite. Reaction wheels and sensors in the ADCS must be aligned properly with respect to each other to provide the appropriate direction vectors.

Figure 6. Preliminary model of the outside structure of DebriSat. This model shows the solar panels attached to the outside and the instruments, such as the antennas and star tracker, assembled on the bottom.

SMEs were consulted regarding current assembly practices to ensure that these practices are implemented in DebriSat. For example, avionics circuit boards may be consolidated together in the center of the satellite in a common shielded box or distributed throughout the side panels in individual boxes. The SMEs have confirmed that distributed avionics boxes are a more common practice.

The components will also be distributed to achieve the appropriate satellite center of mass. Multiple iterations of the design will take place until a representative assembly is achieved.

DebriSat will also undergo space-readiness testing, such as vibration and thermal testing. For example, finite element analysis (FEA) calculations were performed to ensure the structure could withstand a 16G load. This is similar to the load a satellite would experience upon launch.

COST CONSTRAINTS AND DOCUMENTATION

The design of DebriSat was centered on using non-operational components since DebriSat will ultimately be subject to an impact test and due to cost constraints. These components have the same performance specifications as operational ones but may not be held to the same space-qualifications as operational ones. Vendors of COTS components were contacted in search of non-operational parts or parts that were no longer space-qualified. Multiple components were donated or purchased at a discount from space component vendors, which added to the integrity of DebriSat. Other components were emulated based on the acquired components and drawings and datasheets from the COTS vendors found in the public domain.

The documentation process was aided by the bi-weekly telecom meetings with NASA, the Aerospace Company, and the Air Force. For each telecom, status reports were developed that detailed the project's progress and the action items needed. This provided a history of the design process and progress made at each design phase.

The subsystem database and component trends were organized in Excel. A bill of materials and a mass breakdown table were constructed for each subsystem and the overall satellite, which aided in estimating costs and matching the target mass fractions. Cloud storage was utilized to store SolidWorks CAD models, status reports, the subsystem database, and the breakdown tables, which allowed access to documentation for all team members and allowed quicker and easier updates to each document.

OVERALL DESIGN PROCESS

Figure 7 shows the overall design process of DebriSat. The design process was divided into general phases based on the design processes in *Space Mission Analysis and Design*.[5] Although this design did not center on a traditional, functioning satellite, the standard design process can still be applied. This satellite was built to the same performance specifications and standards of a typical satellite, even though it will be non-operational.

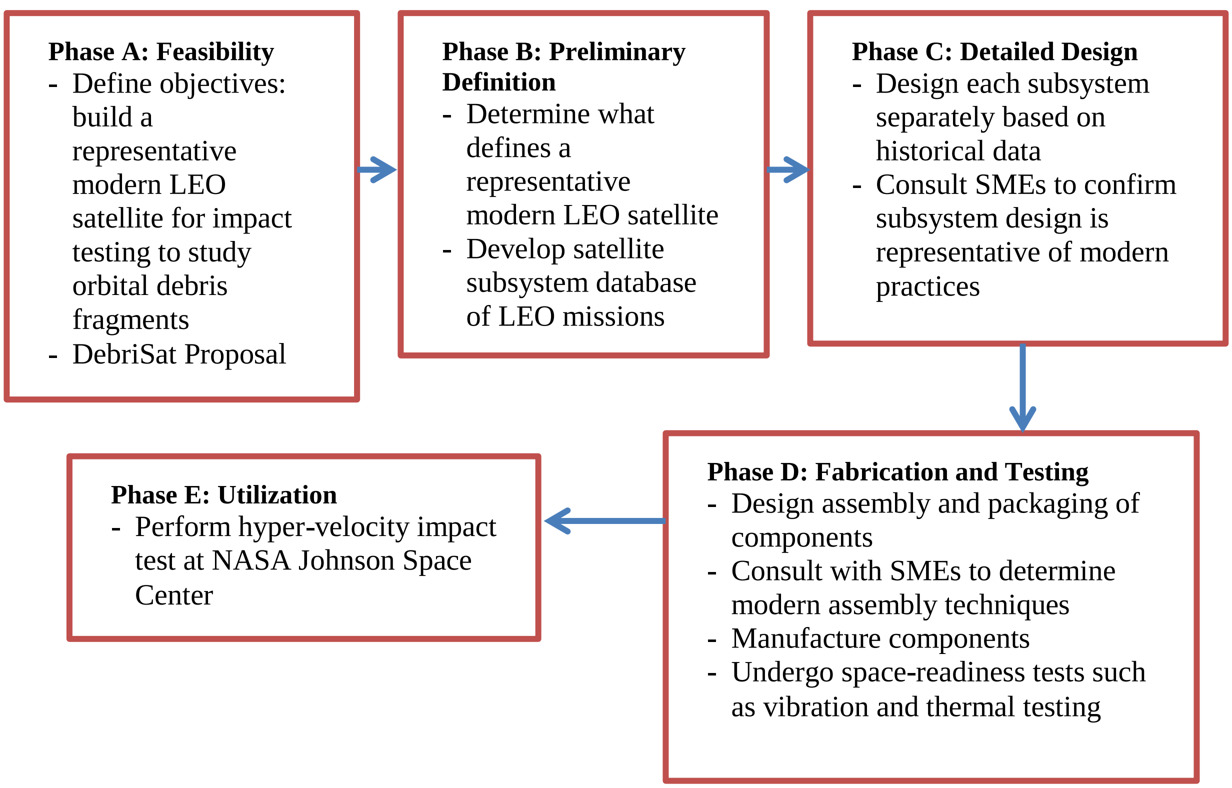

Figure 7. Preliminary model of the outside structure of DebriSat. This diagram breaks down the design process underwent in designing and fabricating a representative modern LEO satellite.

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