An End-to-End Design and Development Life-Cycle for CubeSat Class Satellites

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CubeSat class satellites are being recognized for their potential as utility spacecraft, which can be developed at low cost and in short development time. These factors, coupled with the availability of commercial-off-the-shelf components, have made CubeSats particularly attractive for academia as well as industry, and experimental government missions. However, CubeSats have been questioned for their reliability. This paper presents an approach to increase reliability through rigorous systems engineering practices; an end-to-end design and development life-cycle for CubeSats that implements mission assurance at the various phases of the life-cycle is discussed.

I. Introduction

DUE to aftermaths of natural disasters, terrorist attacks, environmental changes, and other emergencies, there is a growing need for rapid responsive satellites. Current functional satellites in orbit might not be sufficient to respond to such emergencies, thus, new satellites may have to be developed and launched in a short period of time. Compared to traditional larger (monolithic) satellites, smaller CubeSat class satellites could be suitable for rapid responses due to their shorter development time. In addition, due to their smaller size and weight, CubeSat class satellites can be launched at lower costs as secondary payload. This paper proposes a systems engineering based end-to-end design and development life-cycle for CubeSat class satellites. The proposed life-cycle is a modified version of National Aeronautics and Space Administration's (NASA's) project life cycle captured in NASA's Systems Engineering Handbook. This paper also revisits mission assurance definitions by space organizations and presents a case for addressing mission assurance for CubeSats at the various phases of its life-cycle.

A. CubeSats

CubeSats[1,2,3,4] were conceived as educational tools to teach space systems engineering but have, since, transitioned as platforms for space technology demonstrations and science observations. Due to their reduced mass, CubeSats have been launched as secondary payloads, thus lowering the launch cost. The physical dimension of the Poly-Picosatellite Orbital Deployer (P-POD) limited the maximum size of a CubeSat to 3U[1,2,3,4]. However, in recent years, the new specification has increased the size up to 27U[5]. With the new specifications, CubeSats can further demonstrate innovative technology with shorter development times and lower costs. Due to the size, weight and power (SWaP) constraints imposed by the CubeSat specification, their technical performances and design spaces

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have been limited. Furthermore, restrictions and constraints by the launch provider have presented additional challenges to design and development of CubeSats.

B. Project Life-Cycle

A project life-cycle begins with identifying a need then extends through conceptual and preliminary design, detail design and development, production, distribution, utilization and support, and finally phase-out and disposal at the end of a program. Space agencies and organizations have developed and implemented their own project life-cycle definitions. NASA's project life-cycle is divided into seven phases[6]: Pre-Phase A to Phase F. The United States (U.S.) Department of Defense (DoD) project life-cycle is divided into five phases[7,8]: material solution analysis, technology development, engineering and manufacturing development, production and deployment, and operations and support. The International Council on Systems Engineering (INCOSE) project life-cycle is divided into six stages[9]: Concept, Development, Production, Utilization, Support, and Retirement. This paper adapts NASA's project life cycle as a systems engineering based end-to-end design and development life-cycle for CubeSat class satellites.

C. Mission Assurance

In order to ensure high success rate for space missions, it is critical to demonstrate mission assurance through systems engineering. Similar to the project life-cycle, space agencies adopt varying definitions of mission assurance. NASA defines mission assurance as "Providing increased confidence that applicable requirements, processes, and standards for the mission are being fulfilled[9]." The European Space Agency (ESA) defines space product assurance as "To ensure that space products accomplish their defined mission objectives in a safe, available and reliable way[11]." The U.S. DoD defines mission assurance as "A process to protect or ensure the continued function and resilience of capabilities and assets – including personnel, equipment, facilities, networks, information and information systems, infrastructure, and supply chains – critical to the performance of DoD mission essential functions in any operating environment or condition[12]." Although space organizations adopt their own definitions of mission assurance, they all address it across the various phases/stages of their project life-cycle.

II. End-to-End Design & Development Life-Cycle for CubeSats

As previously mentioned, NASA's project life cycle, in particular the scope of each phase, is adapted as the end-to-end design and development life-cycle for CubeSats. A brief review of NASA's project life cycle is presented next followed by its adaption to suit CubeSat missions.

A. NASA Project Life-Cycle

A typical satellite system developed by NASA would transition through the seven phases of its project life-cycle as shown in Fig. 1. The transition between phases is separated by control/progression gates, which are typically, reviews. The Pre-Phase A begins with developing mission concepts, draft of system-level requirements, and to evaluate the feasibility of the system. After a mission concept review (MCR), the project will move to Phase A, where the concept and technology development plan results in final mission concept and system-level requirements. Upon completion of the mission definition review (MDR), the project transitions to Phase B, which is preliminary design and technology completion where the end products are further matured and preliminary concept of operations (ConOps) are also developed. In addition, preliminary software development, such as simulation and analysis are conducted. These first three phases are categorized as formulation and the remaining four phases are categorized as implementation. Successful completion of the preliminary design review (PDR) will lead to Phase C, where the detailed design of the system is finalized, fabrication begins, and early flight software can be developed. Once the critical design review (CDR) is completed, the hardware procurement and software coding commences. In Phase D, assembly integration and testing (i.e., verification, and validation of the components and subsystems) are performed while satisfying system requirements. An operational readiness review (ORR) validates if the system is operation-ready and can be delivered to the launch provider. After successful launch, Phase E involves the day-to-day activities to conduct the mission and to monitor and maintain the system performance as designed and expected. A post-launch assessment review (PLAR) assesses the system to validate mission objectives and operations. During PLAR, it is possible that project may decide on extending the mission. Upon completion of PLAR, project will move on to Phase F, where system decommissioning disposal plan is implemented. Furthermore, this phase will determine the final closeout of the system as well as the result of the mission. A disposal review (DR) will be conducted to determine how the decommissioning disposal plan will be implemented and executed.

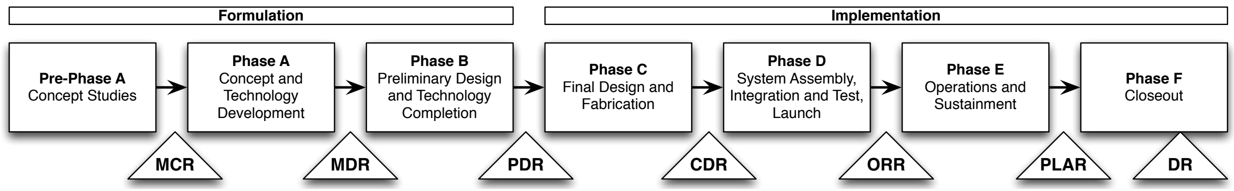

Figure 1. NASA Project Life-Cycle.

B. CubeSat Project Life-Cycle

Unlike traditional satellites, some CubeSat missions are manifested as a mission at a preliminary design stage. At this stage, if the CubeSat mission is a technology demonstrator, the concept technology (i.e., sensors, actuators, science experiments, etc.) is designed, analyzed and in certain scenarios, prototyped as well. The preliminary mission design of the CubeSat serves as a mission concept to perform on-orbit validation of the technology (i.e., it serves to advance the technology readiness level). If the CubeSat mission is a science experiment, the preliminary design captures the payload concept and the mission concept. At this stage, the technology concept or the payload concept for a science experiment are captured in the form of technical articles, (i.e., conference/journals publications) and graduate/undergraduate theses. The preliminary design when presented as a proposal mission to a funding stakeholder, includes an overview of mission cost, schedule, constraints, regulations conformance to CubeSat design specification (CDS)[1], preliminary ConOps, and system budgets (size, weight, and power), among others. For CubeSat missions proposed as secondary payloads on launch vehicle, the preliminary design addresses non interference with the primary payload. Due to the SWaP constraint imposed by the CDS, the design captures these limitations. A preliminary trade study to identify COTS systems, which may include subsystem board, sensors, actuators, etc., is a significant part of this preliminary design. For manifestation, the preliminary design is required to be reviewed and approved by subject matter experts and the funding stakeholder. These activities , which are typically associated with the first three phases of a NASA project life-cycle, are streamlined into a single phase, labeled as Phase AB, and shown in Fig. 2. The streamlining integrates the activities of Pre-phase A through Phase B of a typical NASA Project Life Cycle into Phase AB. The need for streamlining is justified by the finite design of CubeSats, which is imposed by SWaP constraints, COTS components with flight heritage, and space heuristics (past experiences). This streamlining process does not imply eliminating, but rather integrating activities to make the design and development process more efficient and effective.

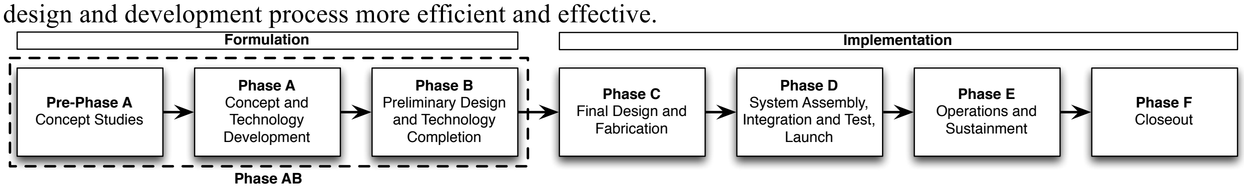

Figure 2. Modified Project Phases.

Upon approval the project, the remaining activities parallel the traditional NASA life cycle process, at best in a highly modified manner (i.e., the overall process structure is emulated, not the specific details). In Phase C, system and subsystem level requirements are finalized utilizing a requirements flowdown technique[6,13], as shown in Fig. 3. The requirements flowdown technique is used to identify and allocate functionalities to subsystems needed to achieve the mission objectives. To add traceability and capture all requirements, a requirements verification matrix (see Table. 1) is developed to show verification methods. Once subsystems are defined, interface control document, such as N-squared (N^2 or N2) diagrams, are developed and finalized. In addition, identifying the available COTS components, if any, and decisions on using COTS or built in-house components are determined. Next, reliability analyses such as failure modes, effects, and criticality analysis (FMECA) and fault tree

Table 1. Requirements Verification Matrix.

No.	Requirement	Verification Description	T	A	O	R
1	A1	Verification of ACS attitude accuracy		X		
2	A2	ADS accuracy	X	X		
3	A8	Satellite total mass	X	X		

T – Test and measurement; **A** – Analysis and simulation;
O – Observation and inspection; **R** – Reference and datasheet

analysis (FTA) are utilized to identify high risk components and aid in the detailed design of hardware and software. Due to the prevalence of COTS components in CubeSats, it is critical that these analyses are performed to manage systems risks[14,15]. Detailed models, such as computer aided design (CAD) models, mathematical models, and physical (prototype) models, are developed and simulated in parallel as detailed designs are finalized. With the detailed design of hardware and software finalized, verification and validation (V&V) testing plans are developed, utilizing the requirements verification matrix. At the end of Phase C, CDR or similar review by subject matter experts not affiliated with the project must be performed. Upon review, procurement of hardware and the assembly integration and test (AI&T) will begin in Phase D. AI&T will lead to requirements V&V as well as adding confidence that the CubeSat will be fully functional in orbit. Once tests are completed, there is another review (mission readiness review, or flight readiness review) by the launch provider to show that necessary tests have been successfully completed. The tests will not only add confidence to the CubeSat itself, but also to the launch provider that the CubeSat will not effect the primary payload and the launch vehicle. After delivery and successful launch, CubeSats will execute their ConOps and data acquisition in Phase E. Once appropriate mission objectives are achieved, the project will moves to disposal phase, Phase F. There are three methods to dispose of satellites; atmospheric reentry, maneuvering to storage orbit, and direct retrieval. Disposals of CubeSats are primarily done via atmospheric reentry. As per CDS document and constraints, CubeSats must be developed using materials that will incinerate during reentry. In addition, CubeSats must satisfy the orbital lifetime requirement of less than 25 years[16].

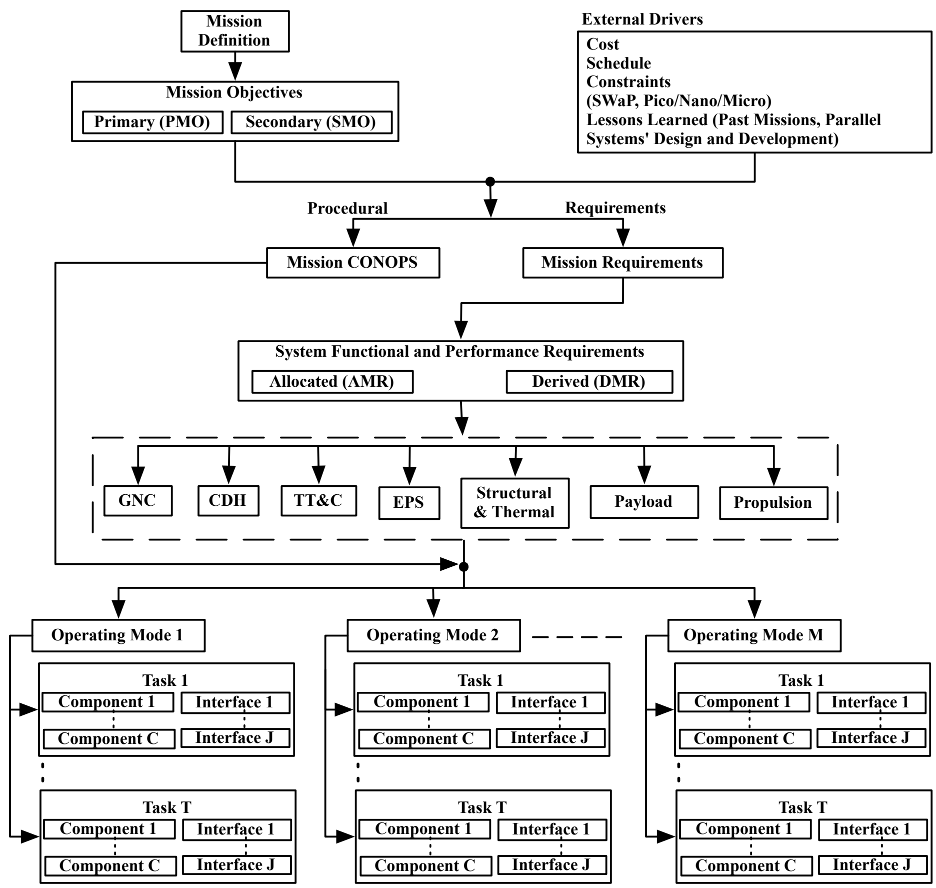

Figure 3. Requirements Flowdown for CubeSats.[13]

III. CubeSat Mission Assurance

Although the number of CubeSat missions has significantly increased in recent times, their utility has been limited. A significant factor, which has limited them as utility spacecraft is their inability to demonstrate mission assurance. An approach, which spans across the above identified CubeSat design and development phases is described in this section. The approach is envisioned to be incremental and as the project transitions to its completion, a 100% mission assurance could potentially be demonstrated. Several key elements are discussed in this section to address and implement mission assurance.

For a CubeSat mission, an acknowledgement of the technology and/or payload design, analysis and prototype is a significant mission assurance factor in Phase AB. Such acknowledgement or artifacts could be in the form of conference/journal articles and graduate/undergraduate theses, that prove the technology concept through experiment and/or analysis.

Another approach to address mission assurance is to develop mission assurance cases, which are written in graphical notations (tree structure as shown in Fig. 4) such as goal structuring notations (GSN) and D-case[17,18]. The top goal/node is broken down into sub-goals to the lowest level. The goal nodes are typically associated with requirements. Furthermore, for each goal/node, context, strategy, evidence and monitor blocks are associated to detail the goal node. Context shows any conditions or constraints of that node. Strategy shows viewpoint and approach used when dividing the node to lower nodes or sub-goals. Evidence shows the basis for assuring the goal node. Monitor shows the content that needs to be checked during operation. An example of GSN and D-Case is shown in Fig. 4. By developing mission assurance cases, each goal node must be verified to ensure the goals are satisfied. The tree like structure of the process facilitates application to very complex systems.

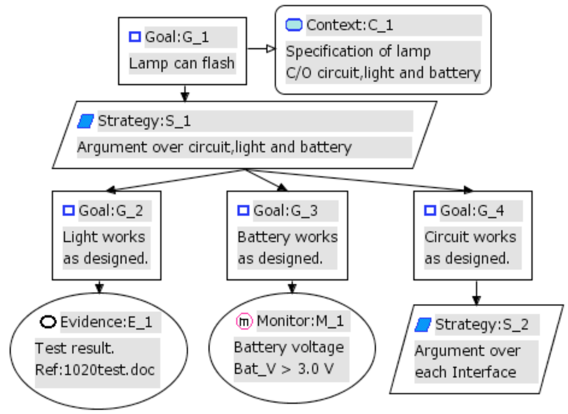

Figure 4. Goal Structuring Notation (GSN) and D-Case.[18]

Another element of mission assurance is verification and validation. Rigorous testing in appropriate environments will lead to adding increased confidence toward achieving mission success. There are various types of V&V, which vary from simulations to developmental testing, and to operational testing. The key for these tests is repeatability. Each tests performed must be repeatable, such that the same tests in same configurations can be performed repeatedly. By focusing on these types of testing at the various phases of a systems engineering driven project life-cycle, mission assurance can be demonstrated for CubeSat class satellites (Fig. 5).

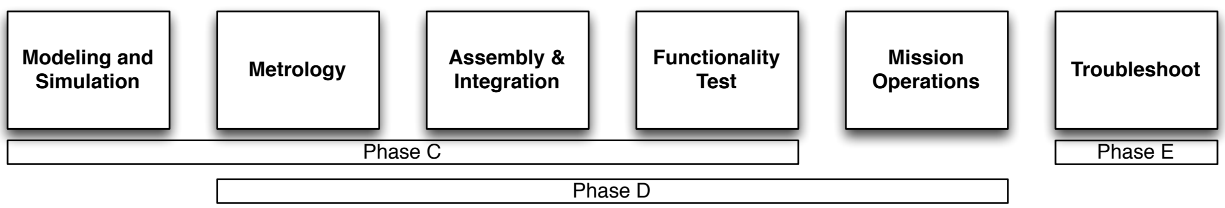

Figure 5. V&V Tests for Various Phases.

Reliability analysis is another element of mission assurance that will lead to increased confidence towards achieving mission success. The primary aim of system reliability is the prevention of failures that affect the operational capability of a system under given conditions. Performing reliability analysis will identify sources of high risk components. Analysis techniques such as FMECA and FTA can be utilized to identify such high risk and possible failures. With identification of high risks and possible failures, mitigation strategies are developed and implemented to reduce and possibly eliminate high risks.

The final element of mission assurance involves rigorous reviews at each phase. Reviews should both be internal as well as external; external reviews should be conducted by subject matter experts from academia, industry, and government organizations, to independently validate the processes and instill confidence in the ability to achieve mission objectives.

Addressing these mission assurance elements, leads to increased confidence in mission success. The following sections will describe in detail how each elements of mission assurance is addressed during each phase of the modified NASA project life-cycle.

A. Phase AB

In Phase AB, the process is too early to perform any verification tests or develop mission assurance cases since the design is only at a preliminary stage. However, proofs of mission concepts are developed and reviews are held. As technology concepts are demonstrated, the artifacts, such as conference journal articles and graduate and undergraduate theses, are disseminated. Internal and external mission concept and preliminary design review should focus on preliminary ConOps and design processes while satisfying CubeSat standards. Successful review will lead to submission of proposal for funding. Approval of the proposal for funding will add more confidence toward achieving mission success.

B. Phase C

As detailed designs of hardware and software are being finalized during this phase, mission assurance cases are developed in parallel while utilizing the requirements verification matrix. The mission assurance cases ensure system and subsystem requirements are verifiable and traceable. Starting with the system requirements at the top, each goal can be decomposed to lower goals. By utilizing the mission assurance cases, V&V and testing plans are identified.

Design verification during Phase C, adds increased confidence. Verifications such as modeling and simulations of the detailed models, metrology and functionality tests of COTS components are performed (shown in Fig. 6). The CAD model and the physical prototype model of the system are beneficial to plan for assembly and integration. The satellite mathematical model with orbital elements and disturbances are used to perform simulations to verify ConOps.

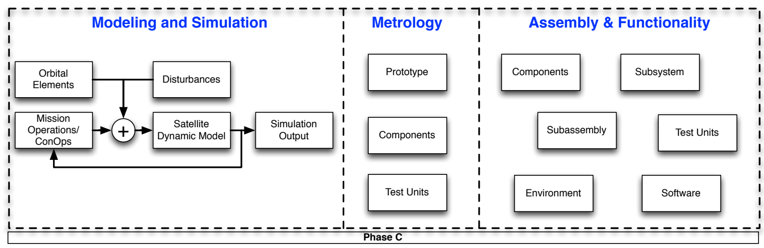

Figure 6. Simulation, Metrology, Assembly, and Functionality Testing in Phase C.

Using prototypes and COTS components metrology and initial functionality tests are performed to add confidence to the final design. Test plans developed from the mission assurance cases, are used during this phase. To perform certain functionality tests, test beds may need to be developed. Moreover, if these components require any software for testing, development of software should commence early in this phase. Once the component arrives, first is to perform metrology on the component. Metrology includes, visual inspection, physical measurements, and electrical testing, if any. Once metrology is complete, the next step will be to perform initial functionality tests. A functionality test can be as simple as powering up the component. On the other hand, some components may require more detailed functionality test. Functionality tests are performed to ensure that the component executes and accomplishes what it is designed for. Multiple components are assembled, such as a sensors and processors to development electronics board, and tested to ensure components will work collectively. Typically, single component failure does not lead to failure of the system, however, several failures occurring simultaneously causes the system to fail. Thus, it is important to test components collectively to ensure that they work together. Some components may not work together, thus, examining compatibility is important. More components are added to a functional assembly and the new assembly is further tested. By continuing to add components and testing functionality, confidence in components and subassemblies will grow and result in the final design. As mentioned earlier, any tests should be designed and performed such that the same tests are performed repeatedly. Same configuration may not be possible (i.e., magnetic field, Sun, etc.), however, it is important that the tests are repeatable. It is also important to perform the functionality tests of these components and subassemblies in different environments, thermal and in vacuum. Utilizing a thermal vacuum chamber, these different environments are simulated. Subjecting the components and the test units to different environments will assure that they will survive and function in the orbit and will lead to decisions on the final design. Performing tests, decisions on whether to use COTS components or fabricate in-house are determined.

Performing reliability analyses on subsystems leads to identification of high risk components. The two most commonly used analytical techniques are FMECA and FTA. FMECA is one of the foundations of all reliability techniques. For each failure mode, effects are assessed and criticality is evaluated based on severity and the likelihood of occurrence. From the criticality, appropriate rigorous mitigation strategies are developed. FTA complements the FMECA by starting with the top-level failure effect and traces the failure to lower potential causes. Results from both analyses identify high risk components for each subsystems and mitigation plans, such as replacing the component or adding redundant component are implemented for the final design. In addition, performing event based FTA on the ConOps leads to developing verification and validation test plans. For example, event based FTA on the ConOps will determine the possible failure causes/components for that operating mode. Utilizing the results, the failure causes/components can be monitored and preventative actions can be taken during V&V. Results from the reliability analyses adds increased confidence towards detailed design of hardware and software.

A CDR or similar review is a key review that must be performed at the end of Phase C. The review should look at detailed design of the system and to ensure that each requirements have been addressed and are properly mapped to design. Furthermore, detailed plans of V&V tests must be in place to successfully complete this phase. External review will aid in ensuring the final design and verification methods are sufficient. Successfully completing the review will add confidence in the final design and lead to Phase D.

C. Phase D

Phase D may be the most important phase for adding increased confidence toward mission success. Most tests and verifications will be performed during this phase, thus, it will be important to spend quality time during this phase. Once the design is finalized, assembly, integration, verification, and validation of the system must be performed. V&V tests in this phase are performed with the help of plans developed from mission assurance cases and requirements verification matrix. V&V tests in this phase include metrology, assembly, integration, functionality, and mission operations (shown in Fig. 7). V&V tests will be conducted at different levels, beginning at component level, move to subassembly, subsystem, and end at system level. The overall sequence of testing is shown in Fig. 8. The objective of these tests will be to verify the functionality and satisfy the requirements. Typically for this phase, there are two identical units that are developed, one is the flight unit and the other is the engineering development unit (EDU). In order to reduce fatigue and stress on the flight unit, the EDU is used on most of the tests. It should be noted that the flight unit must be put through testing as well to ensure the system is functional.

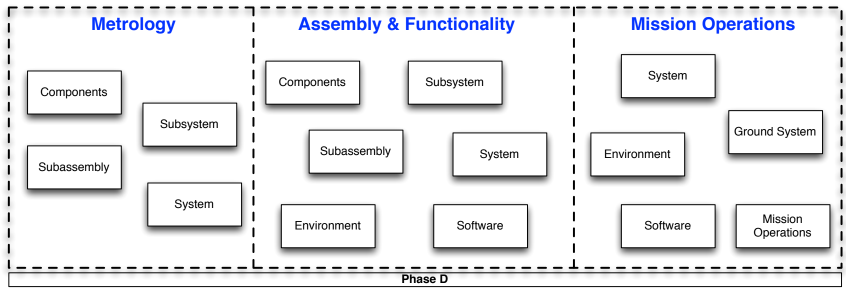

Figure 7. Metrology, Assembly, Integration, Functionality, and Mission Operation Testing in Phase D.

The objective of this phase is to perform rigorous testing at different levels and in appropriate environments. Moreover, in order to emulate operational conditions, hardware-in-the-loop (HIL) tests are performed, as shown in Fig. 9. In these tests the flight software and hardware are exercised to ensure the operability. Results from the HIL simulation are used to modify and update the flight software, satellite model, and mission ConOps. In addition to these HIL tests, environmental (e.g., thermal vacuum cycling, vibrations, and electromagnetic interference) tests are required to demonstrate survivability.

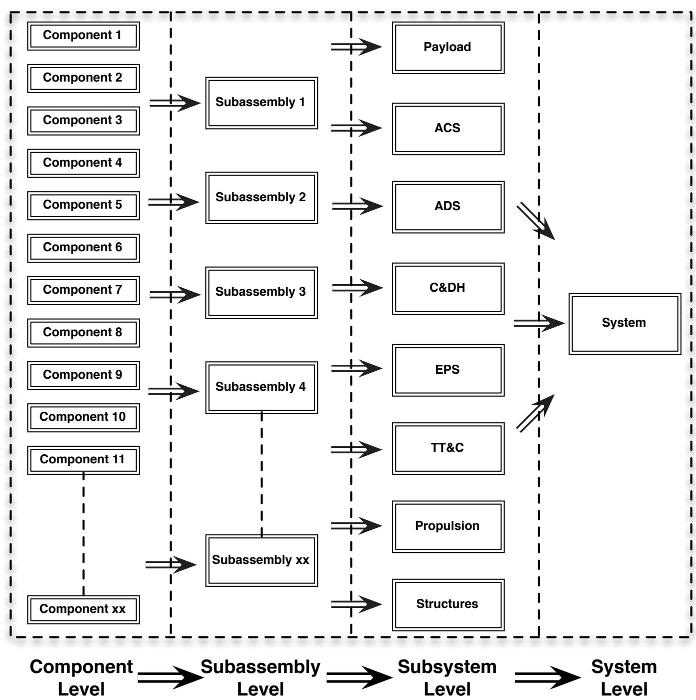

Figure 8. Levels of Testing in Phase D.

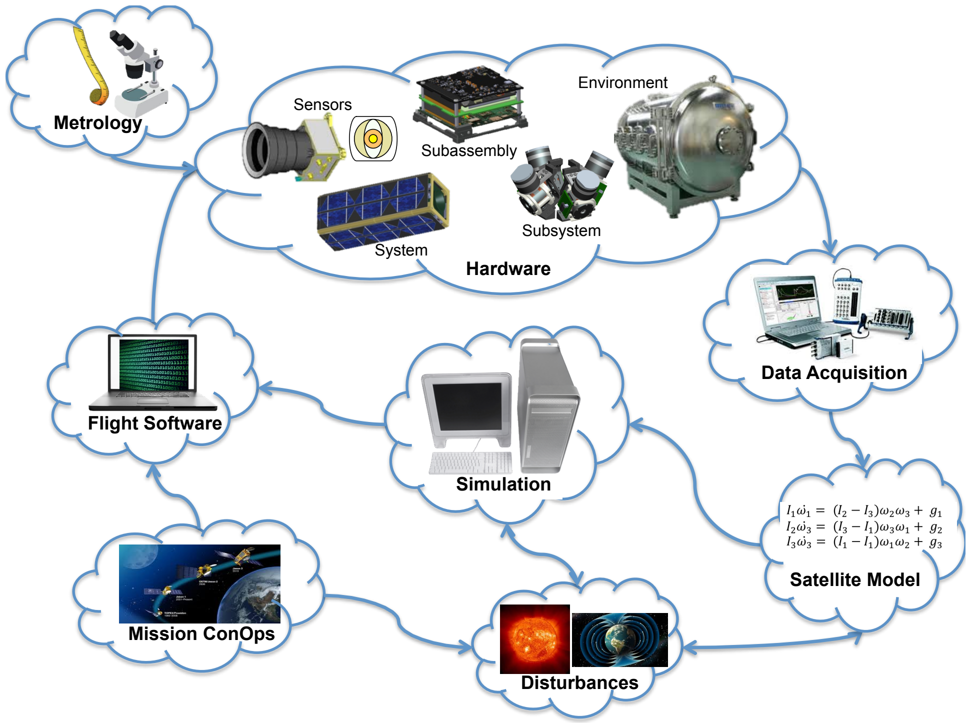

Figure 9. Hardware-in-the-loop (HIL) Testing.

The HIL testing involves multiple tests with various combinations of "real" (flight) hardware/software and emulated components. As components, such as Sun sensors, magnetometers, and star trackers, are acquired, these components should be tested along with supporting emulated systems, such as attitude controllers, flight computer, and power system. Once verification of these components are completed, components are assembled and integrated as subassemblies. As each subassemblies are made, they replace the emulated systems and are subjected to further HIL testing. Upon verification, subassemblies are assembled into subsystems and they are then subjected to HIL testing for verification. This process continues until the entire system is assembled, integrated and verified. At system level, a day-in-the-life test is performed to simulate the day-to-day activities as well as to verify the ConOps. To note, with HIL testing, any hardware (components, subassemblies, subsystems, and system) can be tested at any time.

During HIL testing, mission assurance cases are populated as tests are being completed. For example the evidence nodes for each node are shown as test results. In addition, the requirements verification matrix is used in parallel to verify that all goal nodes and sub goal nodes have been satisfied as tests are being performed. By finalizing the mission assurance cases, proves that all requirements have verified and satisfied.

A mission (or flight) readiness review is performed to ensure that the required tests have been successfully completed. This review should be an external review, which must include launch provider. Most required tests are listed in CDS document (random vibration, thermal vacuum cycling, etc.) however, there may be additional tests required by the launch provider. Successfully completing tests will add confidence not only for the CubeSat but also to the launch provider. A successful review will show that the CubeSat is ready for delivery and launch.

Once the mission (or flight) readiness review is completed, metrology and functionality test should be performed prior to delivering to launch vehicle integration site. During transportation to the integration site, the CubeSat may get damaged, thus, metrology and functionality tests must be performed pre and post delivery.

D. Phase E and Phase F

After successful delivery and launch, by executing and validation of mission ConOps adds confidence toward mission success. It is worth noting that after delivery of the flight unit, other tests that are performed. For example, if problems with the satellite occur on orbit, troubleshooting is performed utilizing the EDU, as shown in Fig. 10. If the failure can be isolated, the same failure is simulated on the EDU and is subjected to HIL testing to understand how the system will behave. If ConOps has to be modified to compensate for the failure, using the EDU in the HIL testing will lead to understanding and addition of confidence in how the CubeSat will behave in orbit. A review during this phase is held to determine the success of the mission. This review is internal and external (if stakeholder exists), where the progress of the mission is reviewed. Once appropriate mission data has been collected or the orbital lifetime has reached, commands to initialize reentry and decommission will be uplinked.

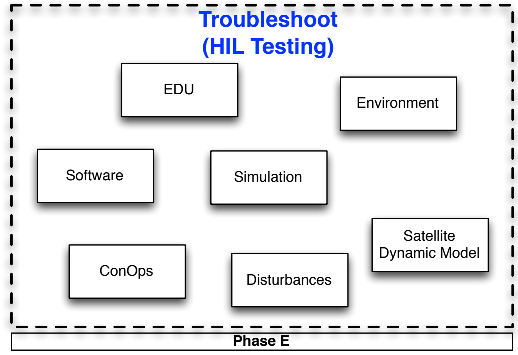

Figure 10. Troubleshoot (HIL Testing) using the EDU.

IV. Conclusion

An end-to-end design and development life-cycle for CubeSat class satellites was introduced. In addition, possible streamlining process utilizing a modified NASA project life-cycle and different mission assurance approach was discussed. To demonstrate mission success, building confidence levels at each phase via mission concept artifacts, mission assurance cases, rigorous testing, reliability analysis, and reviews were shown. The main method to add and increase confidence is to perform rigorous tests at different levels and environments. Furthermore, a HIL testing facility capable of performing end-to-end design and development of CubeSat class satellites needs to be constructed and implemented to address the streamlining process. Such facility will become very useful not only for future CubeSat class satellites, but for future small satellites as well. Further research on refining and improving the streamlining process must be examined. Also, further research and development of metrics of quantification of mission assurance will aid in the end-to-end design and development of CubeSat class and small satellites. However, there are questions that remain unanswered. What is the minimum number and levels of tests that are required? One possible answer is to develop a testing standard such as the Nano-satellite Environmental Test Standardization (NETS) project[19,20] has been developing. A testing standardization approach for not only CubeSat-class but also for small satellites may be useful to add confidence toward mission success.

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