Final Life Cycle Report

Planning the CHIPSat development for the Alpha Project at Cornell Space Systems

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The Life Cycle of the Alpha Project

Why did so many people die when the Titanic sank? One could say it was because no lifecycle plan was made so there was a major shortage of lifeboats available for the Titanic's support stage. To avoid this kind of misjudgment, a Lifecycle Process Report was made for the Alpha mission. By focusing on the entire lifespan, instead of just its utilization, each of the life cycle stages and their implications for the project can be laid out beforehand to avoid overlooking any. These stages include the conception, development, production, use, support, and retirement of the system. In the concept stage, the idea for the product is birthed. This leads to the iterative testing and redesign of the product in development. Production optimises the manufacturing process for the lowest per unit cost cost and time. The utilization phase is when the product is finally installed and used for its purpose. Any maintenance or product repairs are done as a part of the support stage. Finally, a sustainable retirement must be considered such that the product footprint does not lead to additional complications financially or environmentally. These stages have different approaches depending on the customer and market. In this report, the lifecycle of the CHIPSat used in the Alpha project, at Cornell Space Systems, will be considered. Each of the lifecycle stages will be clearly defined for the CHIPSat, along with the correlating systems engineering techniques and models used.

To give background information on the project, the premise of Alpha is to test a light sail propulsion approach. This technology could have the potential to accelerate a CHIPSat embedded system to a quarter of the speed of light. For the Alpha project, the CHIPSat is designed to be lightweight and able to transmit several data points including data from a GPS, accelerometer, gyroscope, and thermocouple. Because of the high risk associated with deep space travel, thousands of CHIPSats will be used, substantially decreasing the statistical risk of failure. These CHIPSats will be stored in a CubeSat container and deployed once in space. The CubeSat is transported as cargo on a rocket headed to the International Space Station (ISS). This lifecycle report will have an emphasis on the CHIPSat itself, because of its intersect with my research. Specifically, I was assigned to write a code for the CHIPSat using a Real Time Operating System (RTOS) to transmit data packets over radio waves in real time.

Concept:

The concept phase begins when an idea is conceived that will solve a problem or need. A mockup of the design should be made and a basic explanation of the system. In formal terms, this means drafting an Annotated Concept Sketch and writing a Customer Value Proposition. These can be used in order to draw in stakeholders and others who will invest or support this product though its development. The next step is to clearly define the system itself, its use cases, and highlight its neighboring systems. Approaching this from a Model Based Systems Engineering (MBSE) perspective, models like the use case diagram and context diagram are helpful in this stage. A use case diagram identifies the uses of the product, both intentional and accidental. The system should be designed robust enough that it is able to be used within not only the directly identified use cases, but also the ones that may happen as a result of interacting with the system. These Use Cases can be shown more visually in a Use Case Behavioral Diagram where the relationships with different users are more clearly portrayed. Next, the product system can be defined in the context diagram. This diagram points out other systems that the product interacts with, and defines a boundary to the system.

For the Alpha project, these models had been made long before the project came to Cornell. The context of Alpha was to test a light sail technology. If successful this would prove that the satellite could be accelerated to a quarter of the speed of light. The light sail concept had many use cases including being able to physically explore a whole new realm outside of our physical universe. This would expand our horizon in the search for life on other planets. Even though the Alpha project had already been modeled, because my work focuses on the CHIPSat design, the concept phase was remodeled in this focused context. A use case diagram, context diagram, and concept sketch were all made, this time specifically for the CHIPSat. These diagrams specified the abilities of the embedded system and the possible limitations of the satellite. In retrospect, the use case diagram, context diagram, and concept sketch laid the foundation of the CHIPSat modeling by defining the where, what, when, and how of the system.

The next step in the concept stage is finding the stakeholder needs and requirements. The first part of this process is gathering the stakeholders themselves. As previously discussed, this is done by presenting the business mission or analysis and gathering interest. Once the stakeholders are found, the scope of the product is bound to adapt. It is important to clearly understand the requirements that the stakeholders have for the product, because they essentially become the contract for the engineering work. This can be done by either expanding the use case diagram or making a requirements table. A requirements table is useful to pinpoint all of the different needs that the stakeholders have for the product. This list should be all inclusive with every requirement the stakeholders have in order to be satisfied with the product. Often the stakeholders are not aware of all the requirements that they have as some are overlooked or assumed. Other requirements may not necessarily be recognized because of the stakeholders' lack of knowledge on the topic. Requirements not originally defined by the stakeholders are referred to as derived requirements. These should also be listed or tabulated. It is the job of the engineer to clarify all of the requirements with the stakeholders.

In Alpha, the sponsorship comes from private donations and crowdfunding. The audience for crowdfunding was largely unaware of the physics nature of the project. However, the majority of the money is contributed by NASA and a few private donors. These would be considered the stakeholders of the project. We are responsible to them for reaching the original proposed milestones for the proof of concept of the revolutionary light sail propulsion technique. This means, in order to continually receive funding, quarterly goals had to be met on our research and development process. Some of the larger milestones for the project included a successful launch, deployment, orbit, and communication with the CHIPSats. The final requirement was obviously to be able to prove the functionality of the light sail. If it failed, we would be responsible for explaining the gap between theory and practice.

Building off of these goals, it is important to develop requirements that have definable and measurable traits. Otherwise stakeholders and engineers could disagree on whether the requirements have in fact been met, and the contract could be voided. Therefore, the stakeholder requirements must be clearly converted to tangible and measurable requirements such that the completion thereof is clear. In addition, the derived requirements should be made clear such that implications or smaller requirements needed to satisfy a larger requirement can be made. For example, if a tool would need a certain power, deriving requirements for its voltage and current could be beneficial. After all of the requirements are listed, a timeline for the completion of the product should be generated. It is appropriate to use a GANTT chart, for example, by listing the requiremenments/tasks and the team member(s) responsible for each one. These tasks are also given individual deadlines such that if all the tasks are done in progression, the project is completed on time.

For the Alpha project, Advisor Dr. Mason Peck laid out a list of requirements that had been agreed upon at the time of the contract. Each engineer in the project was assigned tasks to work on and deadlines for their work. A GANTT chart was made and kept by the senior PhD students. Within my own work, a requirements and derived requirements list were made for the tasks I was assigned. This helped pinpoint what I would have to accomplish and by when. Some tasks included learning the program Code Composer Studio (a version of C++), learning how to write simple programs in C, learning to write an RTOS system and so on. Although these intermediate tasks were not required for the completion of my part, they aided in the development.

Development:

After completing the elements in the concept stage, the development phase is begun. In this stage, the concept is made into prototypes that are tested. Each design is iterated on and streamlined into a final functioning prototype. Starting off, the first part of this stage is the architecture process. In this process a flow timeline within the system is created such that each task or resource can be tracked. This ensures that no resource or step is left out and that there is a logical process to get from the inputs to the outputs of the system. Some MBSE models that assist in this effort are the ICAM DEFinition for functional modeling (IDEF0), Functional Flow Block Diagram (FFBD), or the Operations Description Template (ODT). The IDEF0 is used to break down the flow of resources between systems and classify them depending on their contributions. It is able to zoom in on different stages to understand what the intermediate resources are and to look more in depth. On the other hand, the FFBD shows only one time dependent flow that is more logic based in nature. This model is more focused on the timewise progression of events in the form of a flow diagram. Similarly the ODT is also strongly based on a timeline. The time increases as one progresses down the table with intermittent stages being reached in between. However the ODT is confined to its columns as the only subsystems. After having completed these diagrams, the architecture of the system should be well established.

At the beginning of the Alpha project, a general flowchart was presented showing the progression of all of the transportation mediums of the CHIPSat throughout its trip to Alpha Centauri. The model showed use of the architecture process by the way that it defined the development of events throughout the deployment of the satellite. After working on this project, the architecture was able to be strengthened through systems engineering diagrams. The IDEF0 was specifically helpful in this process because of the many functions that the CHIPSat would have to go through. The tasks of the CHIPSat could be broken down into its launch, deployment, space travel, and the measurement and transmission of the data. The FFBD was used in order to break down the commands that would be needed in the code of the CHIPSat. It helped map out the logic used to develop a functioning code, based on a time dependent progression. Modeling the CHIPSat this way proved highly important in making sure every process was sound from start to finish and understanding the order of execution.

The next step in the development phase is the integration process. The development phase lays out how the prototypes will be built. This is done initially to provide a preliminary evaluation of the product, a rough design idea, and budget. In this stage the annotated concept sketch can be updated to a diagram or a drafted CAD (Computer Aided Design) model. Having this model will make it possible to fabricate all of the necessary pieces needed for the development. This model will change as iterations are made to the design. Every model should be saved separately to be able to trace back to earlier revisions of a design, and to show the progress or evolution of the concepts. In addition other models for decision making can be used. Using a Goal Question Matrix (GQM), a decision matrix or a Quality Function Deployment Matrix

(QFD) make it possible to weigh decisions in order to come up with the best design solution to meet the functional requirements.

The Alpha project has many CAD drawings that aid in the understanding and development of the CHIPSats, CubeSat, light sail and any other subsystems involved in the project. These aim to give a tangible design to every element in the system and visibly simulate how they act in coherence. For example, in the opening of the CubeSat, deployment of the satellites, and unfolding of the light sail, a CAD simulation is helpful to identify possible hangups both figuratively and literally. In addition, analysis can be done to make sure the design fits the engineering criteria before fabrication begins. This is often done when choosing a material for a part. Many different materials can be tried and tested within the CAD theoretical environment. Another method of decision making is the Decision Matrix. Specifically, for the CHIPSat, a Decision Matrix was used in order to determine which sensors should be incorporated in our design. By using this matrix, sensors most appropriate for our application could be determined.

The integration process comes next in the development phase. This process works on integrating the system so that all of the interfaces interact seamlessly. Integrating can take on a lot of different forms including integration within the development stream, incremental integrations in the design, or integrating the system globally. Considering this in the development phase once again (as opposed to originally in the concept stage) is worthy because of the possible design changes that may have occurred. Having a more tangible idea of the product and its abilities may also inspire new ways to adapt certain features or broaden the way a customer interacts with the product. Once these changes have been implemented, prototype integration can be achieved one of three ways: from the top down, from the bottom up, or using a criteria diven method. The top down and bottom up methods both work progressively through the design levels, but in reversed orders. The criteria driven method, however, starts at the criteria and builds a system basis around it. A final facet of the integration process is the ability to reorganize and regroup matrices with components or systems that work well together. To model this, an N squared matrix can be created. This matrix can be reorganized by grouping the elements near the diagonal. This can create clusters of identifiable subsystems that undergo extensive interaction.

The Alpha project has had to focus extensively on the integration process. The system must interact with a lot of foreign systems or environments including a rocket, the ISS, different operators, and the harsh environment space provides. Some internal interfaces can be made simpler by restructuring the system. For example, in the CHIPSat code, an N squared diagram was used to group functions within the embedded system that would interact more frequently. This made it logical to write the programs such that these elements could use similar functions to condense and streamline the software. Throughout the design process, a bottom up development was used. This method made it possible to identify all of the components and link them to centralized sources like the solar panels, analog to digital converters, transceiver, and processor. In addition, making sure the design is well integrated into its environment is a high priority. This could be done by artificially recreating different environmental threats the CHIPSat might find itself in and observing its behavior. It is important that not only is the integration of subcomponents flawless, but also the integration with the other exterior systems it depends on.

Continuing on in the development phase, it is very important to understand the difference between verification and validation. Validation is defined as how your customer will judge your product or, in simpler terms, the overall product quality. Essentially validation measures how viable the system is in solving the customer's problem. It is tested by checking that the requirements have been fulfilled. This can be done using either a Behavioral Test Plan or a Test Methodology for every requirement listed. The Verification Cross Matrix Reference (VCRM) can be checked to match each test procedure with its requirement. Verification, on the other hand, is checking that the system is functional in and of itself. This means that everything works as it was designed to do. Verification can be tested in the GQM. In other words, validation is making sure you are solving the correct problem while verification checks that the way you solve it is valid and will work as intended. As could be inferred, both of these criteria must be met before advancing to the production stage.

Most of the model based systems engineering diagrams have some component of verification or validation incorporated. For example, the functional requirements, use case diagram, interface matrix, and requirements table all have a strong focus on validating the product. These models hope to point out if the system will act as intended and what are unforeseen interactions or complications the system could have. On the other hand, the derived requirements matrix provides a summary of metrics that can be used for verification. Other models include the Verification Cross Reference Matrix (VCRM) or and the Analysis Inspection Demonstration Test matrix. These matrices work to prove that a part of the system is functional through measured testing.

It was more difficult to find examples of validation within the Alpha project. Because of the research nature of this project, it is more focused on the development of a new technology, so the capabilities of the project are constantly changing. If it were to be put in the confines on the basic requirements, however, the mission of the Alpha CHIPSat project is to create a solution for a feasible transportation medium that could allow scientists to reach the stars. Reflecting on this requirement, the lightsail approach has this potential and will hopefully render the Alpha mission Valid.

Verification is much clearer within the Alpha mission. Every piece and part of the CHIPSat and CubeSat have or will be tested for all conditions that they could experience in space. A NASA contractor is also assisting our testing efforts. This contractor is responsible for verifying that our system will not negatively interact with any other systems in space. Examples of threats our system pose include overlapping communication channels or collision damage if our system is off course. Verification also takes place in the CHIPSat code. This happens extensively when updating or uploading the software to the CHIPSat code. Being able to test early and often is crucial in catching and fixing mistakes promptly.

The last step in the development phase is the implementation process. This process goes through the preparation of implementation, the implementation itself, and managing the results of the implementation. This process proceeds all of the other development steps, and outputs an implementation strategy, requirements, and constraints as well as documentations such as records and reports. This would include any steps to implement the product where it will be used and assembling documents on how to achieve this. This often comes in the form of directions for the consumer.

For the Alpha project, the implementation process has not yet occurred. What this process might look like for Alpha, however, is putting together the system and preparing it for deployment. This would entail packing the CHIPSat in the CubeSat, and the CubeSat in the NASA rocket. Once this implementation occurred, the next step would be to include proper documentation of the deployment process. This makes for a smooth transition from the manufacturer to the consumer.

Production:

The production stage repeats the validation process to ensure that the system follows the requirements and customer needs. This means revisiting both the original and derived requirements and testing these using the VCRM with the Behavioral Test Plans and the Test Methodologies. Each Behavioral Test Plan and Test Methodology should be listed in the VCRM with the appropriate requirement they will be testing. Another validation strategy is using a Failure Mode Effect Analysis (FMEA) to assess the largest risks associated with the system. These risks should also be evaluated on their severity and likelihood. With a Risk Priority Number Table, each risk can be plotted to objectively reflect their threat to the system. Each risk should be low or managable in order to release the product.

In the Alpha project, both Behavioral Test Plans and the Test Methodologies were used in a VCRM. Some specific tests include the testing of the burn wire, the deployment of the CHIPSat, and unfolding of the light sail in a vacuum chamber. Additionally, a balloon test is planned in order to test the radio transceivers and make sure we can make contact with the CHIPSat at a high altitude. After completing these tests, the risk can be determined using the FMEA. The Risk Priority Number Table will determine if we can move on to the utilization phase.

Utilization:

The next phase of the product life cycle is the utilization phase, where the product is in the possession of the consumer. This begins the part of the lifespan where the product has been sold and is no longer in the stakeholders possession. The utilization phase can be broken up into two sub stages. The first is the transition process. The transition process is defined as the phase where the product or system is being implemented for use. This could mean assembling a system, transporting a system, or simply removing it from its packaging. The inputs to the transition stage will include the final Requirements Verification Traceability Matrix (RTVM), a verified system, and a validated system report. This includes event and fault trees that can aid in the choices made while installing or setting up the system. The installation may also require calibration of elements or sensors. At the end of the transition phase, the system should be fully functional in its intended environment and ready for use. Some outputs of this stage are creating a transition procedure (as practiced in the PBandJ assignment), and any transition reports, records, or training materials that may need to be referenced later on.

The transition phase is fairly long and difficult to define for the Alpha mission. It is clear that this will include the calibration of each of the sensors, packing all of the CHIPSats into their respective CubeSats, and loading the CubeSats into a rocket. The transition phase of the Alpha project ends there. However the CHIPSats will not finish their transition phase until they have been deployed in space, and the light sail has unfolded. This stage of the lifecycle process has not been reached yet for the Alpha project. Therefore, a final RTVM has not yet been made. However, a decision tree has been made such that the operator is able to control the CHIPSats appropriately after launch. This will be important as actions will have to be made in quick progression after launch.

The next stage within the utilization phase is the operation process. As the name suggests, this is the part of the lifecycle where the product is in operation. Proceeding the operation phase, training may need to occur such that the operators are able to use the product as intended. In addition a maintenance report should be provided for the support stage, such that proper care can be taken to increase the products lifespan. The system should provide a net positive utility or financial net gain. This means that the operation phase should provide a higher net gain than the investment development of the system. Coming out of the operation process, an operation strategy should be developed such that the functional purpose or lessons learned during its operating lifespan are documented. Including an operational report or record can also show the yield throughout the given time period. This makes it possible to analyze and understand what factors cause the system downtime.

The Alpha mission will spend its whole utilization phase in space. This means that it will not be physically accessible to its operators. It is important that the operators are properly trained on how to communicate with the satellites. This will be even more relevant because as the satellite travels, commands will be days, weeks, and eventually even years out of sink due to the speed of communication over radio. The information that will be retrieved from the satellites will be able to be processed to learn more about the travel of the satellites and what these systems are capable of. In order to guarantee reliable data for the operation reports, the data sent will be encoded to check against doppler shifts that the data might encounter.

Support:

During the utilization phase, a support phase is often necessary for both maintenance and fixing of any parts of the system. This becomes prevalent for products sold on a large scale to private entities. The support stage increases the utilization lifespan of the product. Some basic examples of support phases people interact with in everyday life include mechanics and technicians. For product developers, the support stage can be an opportunity to record any recurring failures. Going back to the development phase, these issues can be fixed and a new updated model released.

The Alpha project does not have a support phase. This is because the CHIPSats will be inaccessible after launch. If any hardware changes must be made, that would have to be implemented in a different launch or project. Software changes could theoretically occur. However, implementing these changes from such a far distance adds an immense risk. The mission essentially relies on getting everything right before the launching of the satellites. This is why the mission hopes to model utilization lifecycle similar to that of an r-selected species. R-selected spawning in biology is a regeneration technique usually used by smaller creatures with a low chance of survival. To combat the large infant mortality rate, the creature produces a very large number of offspring in order to statistically guarantee the survival of a few. In a similar way, because no corrective action is possible after deployment and the journey of these satellites is long with many known risk factors, by deploying thousands of satellites the Alpha mission plans to statistically promise the success of at least one satellite.

Retirement:

The retirement stage is the final stage of the product life cycle. This is defined as how the product is properly disposed of. IT is also an appropriate time to reflect on the lessons learnt, such that improvements can be made in other projects. Often in the life cycle the retirement state is left out or forgotten, however it can be one of the most important stages. First off all, a sustainable disposal should be considered. This means taking into account environmental and societal burdens that the disposal of the product may incur. Designing a system with parts that can easily be separated is crucial. This means creating parts of pure materials, such that components can be biodegraded, or reshaped for reuse. Reusing materials puts the “cycle” in “lifecycle”. Looping back to the concept stage, many companies are shifting to sustainable production by reusing materials from previously retired projects. If a product can be appropriately retired, it becomes possible for its materials to be reused in another lifecycle.

Secondly, the lifecycle of the system should be recorded. In order to build better systems or advance a technology, the shortcomings must be identified. One of the most valuable parts of product design is identifying the things that work, the things that did not, and pieces that could be improved upon. Drawing from the operation phase, the downtime of the system should be examined, and large inefficiencies minimised. By analyzing the operation reports, new areas of improvement can be identified. Building on these in a new iteration can guide development towards a more efficient system

For the Alpha Project, a recovery of raw materials was not included in the retirement phase, because of the difficulties in recovering it. Although CHIPSat material will not be able to be reused after deployment, it will be disposed of properly as space debris several light years away from earth and will pose no threat to our environment. In the long term, the plan is to develop a technique so the CHIPSats can use the light sail to eventually propel themselves back towards Earth. This is a topic of research Dr. Mason Peck has been developing. Similar CHIPSats could be used to transfer large quantities of data physically by reentering the earth's atmosphere. For future CHIPSat missions, this strategy could be implemented such that the CHIPSats could be entirely reused.

In conclusion, it is important that products be designed with these stages in mind, to ensure a safe and successful product. With Alpha, we will use these guidelines in hopes to achieve a successful mission. It is our goal that the data acquired and technologies developed will carry well beyonds the lifespan of the CHIPSat.

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