Literature Review

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1 Introduction

Quality modelling and simulation tools are critical to the success in the development of any aerospace system. When applied according to model-based system engineering (MBSE) practices, these tools allow a designer to verify system-level requirements early in the design process, reducing the cost of changes that would otherwise be made later in the development cycle. One such modelling tool is the Horizon Simulation Framework (HSF). Developed over time by Dr. Eric Mehiel and a group of Cal Poly graduate students, HSF is an open-source simulation tool that allows users to input a model and an environment to ensure a system concept can meet levied requirements. One potential application of HSF lies in the modelling of formation flight of multiple spacecraft. As weight onboard a launch vehicle is at a premium, there exists great potential in dividing otherwise large monolithic space systems into multiple smaller craft that can work together to achieve comparable or improved performance. While the origins of the concept trace back to the dawn of the manned space program, there has been significant interest in the development of formation flight applications in the past two decades. A novel application of formation flight that this thesis will explore is that of a small satellite-based interferometry array. The use of interferometry is foundational to our understanding of the universe. Whether it be applying synthetic aperture radar to examine the details of the surface of our planet, or infrared sensing to characterize far away worlds, the applications of interferometry are innumerable. With this in mind, the objective of this thesis is to use the Horizon Simulation Framework to successfully model a day in the life of a small-satellite based interferometry array in formation flight.

2 Model Based Systems Engineering

Model Based System Engineering is an iterative approach to system engineering that applies modelling to support system design, requirement definition, and verification and validation activities of complex systems. This engineering discipline is broad in scope and can be applied at all stages of a system life cycle: from concept, development, production, to operation phases [1]. By integrating model driven data to the system engineering process, defects in design can be detected earlier in the life cycle, resulting in reduced cost.

Models are representations of the overall system that link design concepts to how they would be implemented [2]. Using them in a system engineering context allows for an engineer to consider the entire engineering problem, use standardized language to describe the problem and solution, produce a complete solution, and comprehensibly verify that the solution meets all system requirements.

The aerospace industry is currently undergoing a transition from the document-based engineering practices of old to MBSE of the future. Traditionally, system engineering relied heavily on various documents in many form factors including texts, visual diagrams, and spreadsheets. The spread of information in this manner leads to a lack of precision, inconsistencies between resources, and makes traceability more challenging throughout the design process [3]. Under this paradigm, changes in a system design must be manually validated leading to a higher likelihood of error. On the other hand, MBSE clarifies the definition of relationships between system engineering elements thus providing better traceability that can be automated, ensuring global consistency in a design. What was before disparate sources of information can be consolidated into a global model that promotes a better understanding of the system as a whole. This improved perspective allows for a more programmatic approach to validation of requirements.

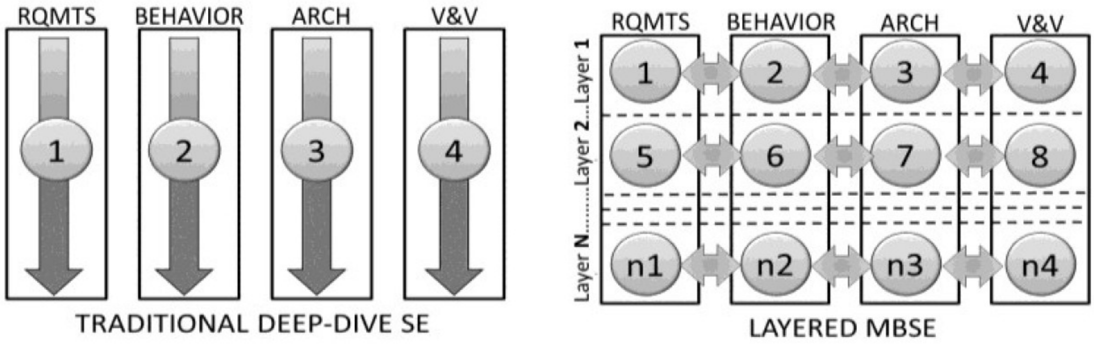

Figure 1: MBSE Layered Approach [1]

Another feature of MBSE is the nature of the layered structure it provides the design process. As the system iterates through the development process, more details about the system as they are determined are captured in successive layers with each layer increasing in specificity and resolving unknowns. As the methodology progresses, focus is placed on understanding the interactions between requirements, subsystems, and the system and its environment, before moving to the next layer of complexity. As described by David Long and Zane Scott, these interactions can be captured in four domains of system engineering: requirements, functional behavior, architecture, and verification and validation [1]. Requirements are statements about what functions the system must satisfy to meet stakeholder needs. Functional behavior is what the system will do to achieve levied requirements. Architecture is the physical layout of the system that offers balance in ease of manufacturing, testing, and support all while complying to requirements. Finally, verification and validation are processes to ensure the developed system successfully fulfils the given requirements and that the customer and other stakeholders are satisfied with the end product. A key tenant of MBSE is the progression through these disciplines in concert with each other as opposed to a traditional approach that would drive work in understanding each domain individually in parallel. In the traditional approach, iteration between the domains often requires significant reengineering of the design to account for changes made in the iteration thus increasing expense. This layered methodology allows for each domain to be considered with greater context, combating a classic design mistake of losing system context. As the MBSE approach is progressed, each layer of the system design is completed thoroughly by addressing all domains. This meticulous approach ensures that a design solution is converged on.

3 The Horizon Simulation Framework

The Horizion Simulation Framework (HSF) is an MBSE tool developed by Dr. Eric Mehiel and a group of past Cal Poly graduate students to model the behavior of complex systems for verification of system level requirements. The software was designed with a focus on modular, low fidelity modelling for the purpose of constructing a day in the life of the system [3]. This emphasis on modularity allows a user the ability to make updates to elements of their system model without significant rework of the overall model [4].

In this spirit of modularity, HSF is largely made up of two portions: modelling and scheduling. The division of these portions allows the user to customize the modelling elements to their use case and the scheduler will understand how to handle the information. The modeling portion requires users to define subsystems, dependencies, constraints, and initial conditions. A subsystem is a modelling element that preforms tasks and maintains a state, dependencies are how subsystems interact and pass information between one another, and a constraint is a limit on the range of states that a subsystem can take to ensure that the subsystem can perform a given task [5]. As of version 3.0, the HSF scheduler takes advantage of branch-and-bound dynamic programming [6]. For a given time step, a list of all possible events is generated which the system then evaluates to determine valid schedules that the system is capable of preforming. When a new schedule contains a previously generated schedule, the old schedule is referenced via a pointer. This allows for better computational efficiency as the referenced schedule does not need to be stored or evaluated repeatedly. Further reduction of computational waste is achieved by defining a maximum number of schedules considered. To rank the options, each possible schedule is passed through an evaluator that uses a cost function to determine a performance score. Only the best preforming schedules are considered.

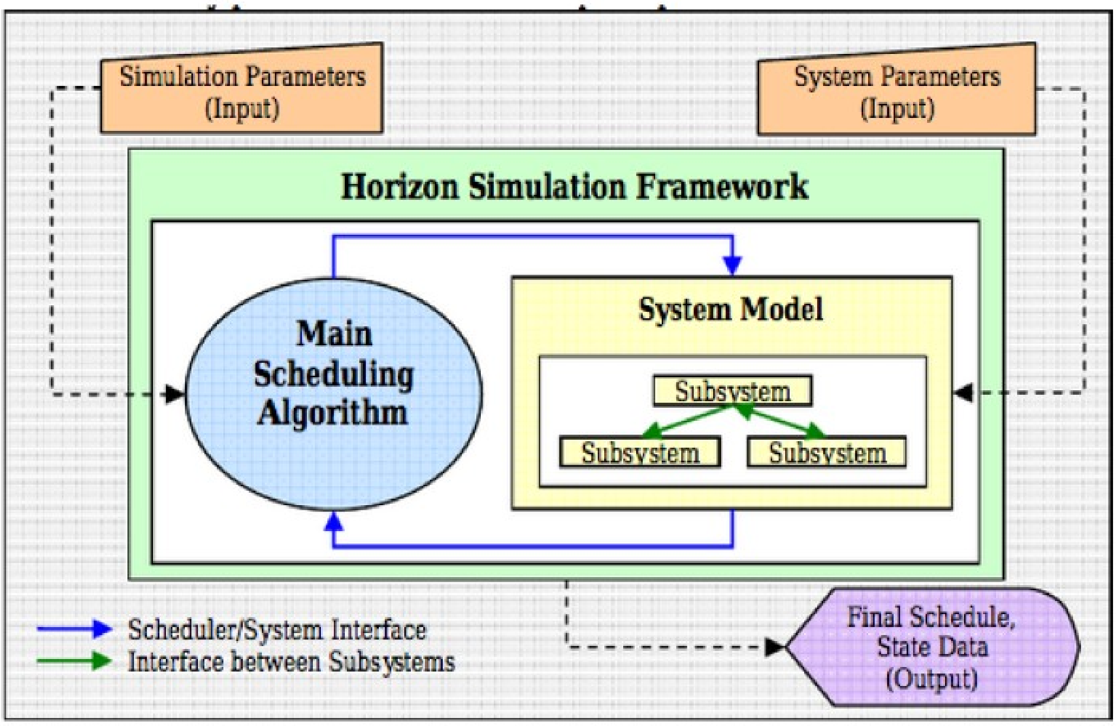

Figure 2: HSF Elements [4]

An important aspect of HSF is that it is open source. Open-source software allows users to freely modify an existing codebase, use the software in new ways, and incorporate the results into a derivative work. This is opposed to proprietary software where the manufacturer restricts users from altering code or using the software in unintended ways. The removal of barriers between the developer and user fosters a more collaborative environment that promotes the exchange of ideas and innovation. As a result, the software is improved over time by a community of contributors, often at a rate faster than a closed team could achieve. While there are many advantages to making a software open-source, there are also corresponding challenges. With a growing body of contributors, there exists a growing need for guidelines and standardization to ensure that once code is merged, the software feels unified. To address this concern, HSF implements source control by requiring contributions to pass unit tests.

There is an ever-growing body of work conducted developing and utilizing the modelling capability that HSF offers. Presented at an AIAA conference in 2008, O'Connor, Mehiel, and Butler progressed the software to version 2.1 allowing for the modelling of multi-asset scenarios and developed a baseline test case called the Aeolus Constellation in which a pair of Earth imaging satellites were simulated [4]. In 2009, Mitra Farahmand implemented four orbital propagators to HSF: Two-Body, J2, J4, and Simplified General Perturbations 4 [7]. The results of the propagations were then compared to MATLAB and Systems Tool Kit models to ensure accurate implementation. In 2010, Zhenhua Li used HSF to simulate a small unmanned thermal glider [8]. A thermal environment was created, and the corresponding flight dynamics of the craft were simulated with the goal to enhance the fidelity of modelling in the field of thermal navigation. Also in 2010, Brian Kirkpatrick developed Picasso, a visual interface that allows users to control input files to HSF [9]. Picasso also allowed the visualization of HSF outputs. In 2016, Ian Lunsford continued development by implementing a feedback system that produces .csv files to list subsystem failures and constraint violations [5]. Also in 2016, Shaun Luther introduced the ability for HSF to understand models designed using the popular MBSE tool Systems Modeling Language (SysML) [3]. The Aeolus test case was translated into a SysML input script, and the results were then compared to the original baseline developed in 2008. A SysML model of the Cal Poly CubeSat mission ExoCube was also developed and implemented within HSF to demonstrate future scalability. A year later in 2017, Steven MacLean used HSF to model an active control system of a sounding rocket using LQR control theory [10]. The simulation sought to determine the effect of the control system on achievable altitude. In 2018, Adam Frye used HSF to model a UAS swarm of fixed wing craft for the applications of search and rescue and reconnaissance operations [11]. Most recently, in 2019 Alex Johnson used HSF to simulate the CubeSat Astronomy Network, a constellation of small satellites focused on astronomical research for undergraduate and high school students [12]. HSF simulated a day in the life of the constellation to assess design feasibility.

4 The Future of Formation Flight

One of the most exciting concepts coming to market in the aerospace industry is that of formation flight. The use of multiple satellites in concert significantly improves our ability to collect scientific information. Dividing an otherwise monolithic system into components allow each component to be smaller, lighter, and typically simpler. Smaller satellite elements offer unique advantages over traditional larger ones as they are cheaper to develop and launch thus offering ideal technology demonstration platforms. Dividing elements of the flight system among multiple small satellites in parallel can allow for the overall system architecture to be more fault tolerant as individual elements can be more easily replaced [13]. Many smaller craft in formation taking various data can be managed more effectively in a formation, using fewer resources on the ground.

While there are many advantages to formation flight as a concept, there are similarly many challenges facing its development into mainstream use. Depending on the proximity and resolution of the formation, propulsion concerns exist as the reduced size of the craft limits on board propellant storage as well as the propulsion types available. As a result of these concerns, the time scale of formation flight missions is often restricted.

Despite these challenges, there exists a significant legacy of formation flight being used in space. Some of the earliest forms of formation flight date back to the Gemini missions in which rendezvous and docking spacecraft in orbit was first attempted. There exist many examples of formation flight in orbit today. The GRACE mission launched in March 2002 and carried twin satellites designed to examine earth gravity field anomalies [14]. The pair of satellites flew an identical near polar orbit separated by 220 km along track. By examining the changes in their relative distance as their orbit passed them over different regions of the earth, information about the earth's mass distribution can be deduced. The orbit of the pair of satellites allowed them to obtain global coverage every 30 days. Outlasting an initial 5-year projected lifespan, the GRACE mission was operational for 15 years before end of life in June 2017. The success of the mission prompted an experiment follow on mission labeled GRACE-FO using much of the same technology previously developed and flown. Launched in May of 2018, the new pair of satellites continue to map the Earth's gravitational variations, now equipped with a first of its kind laser-ranging interferometry device used to determine the relative distance more accurately between the crafts.

On a smaller scale, the CubeSat Proximity Operations Demonstration (COPD) mission launching in late 2021 will consist of 2 3U sized CubeSats weighting 5 kg each [15]. Both flight elements will seek to demonstrate the maturation of rendezvous and proximity operation of small satellites including docking. This will be accomplished using a propulsion system consisting of a liquid fuel tank and 8 nozzles to support 3-axis translational control [16]. Power will be supplied by two deployable solar arrays and docking will be completed using electro-magnets. The payload is designed to be stowed in a 6U configuration before on orbit separations and proximity operation. Maneuvers will progress in terms of complexity and associated risk by gradually turning off targeting LEDs to validate sensor performance under varying light conditions. Many of these operations will be conducted autonomously relying on on-board sensors and processors to determine GNC. Many byproducts of this mission will enhance the capability of small satellites to work with one another to accomplish goals that they could not complete individually.

5 Small Satellite Based Interferometry

Interferometry is a concept fundamental to humanity's understanding of our world and its place in the universe. This technique merges two or more sources of waves to create an interference pattern which can be analyzed to determine information about a distant target. Interferometers come in various shapes and sizes as they are built to handle different portions of the electromagnetic spectrum.

Two examples of interferometer applications that see use in space are infrared systems that look outwards to identify potential exoplanets, and synthetic aperture radar systems that look back towards earth to collect data on various terrestrial characteristics. The mid-infrared range from 5 to 20 micrometers offers a wealth of pertinent data useful in characterizing exoplanets including size, orbital characteristics, temperature, presence of an atmosphere, and presence of significant biomarking atmospheric molecules [17]. Observations on this wavelength are impossible from the ground due to intense atmospheric attenuation, thus are best suited for a space-based system. It is expected that in order to characterize solar systems within 10 parsecs of Earth in this spectrum, an aperture of at least 80 meters in diameter would be required, something that would be impossible to achieve using current monolithic observation platforms but may be possible using an array of formation flying satellites. Looking in the opposite direction, synthetic aperture radar (SAR) has a flight legacy of detailed mapping of the scattering properties of Earth's surface. Unlike infrared sensing, SAR is an active sensor, meaning it does not require an external energy source like a star to collect information [18]. The analysis of a backscattered radar signal allows for high-resolution imagery of an observed area. SAR interferometry (InSAR) determines a phase difference between two or more SAR images captured from different positions and/or at different times [19]. Configurations of InSAR are generally categorized as: across track interferometry in which images are captured from different positions at the same time, along track interferometry in which images are captured from the same position at different times, or repeat-pass along- track interferometry in which images captured at different times from different positions are compared. These methods allow for the study of the dynamics of the Earth's surface and the development of deformations over time.

Both methods of interferometry described take advantage of their location in space as opposed to ground-based sensing systems. Wavelengths can be examined that could not otherwise be captured from the ground [20]. Long term observations can be completed that would otherwise not be possible due to occultation or solar eclipse. A more stable environment allows for easier alignment and calibration of sensors as well as better vibrational isolation. Reconfigurations of the observation array are generally easier and quicker to do in orbit than on the ground. While there are many benefits of a spaced based interferometer, there are also significant challenges to overcome, particularly the expense of development, emplacement, and operation of such systems and difficulty in accessing them once on orbit should something go wrong. In specific to small satellite-based interferometry arrays, additional challenges appear in achieving the required precision of initial orbital emplacement of an array, ensuring the array elements maintain precise formation control, and propulsion systems that are safe for low-thrust trajectory adjustments in close proximity to other flight elements.

The concept of formation flight interferometry has seen success to date. The TanDEM-X digital elevation model is the accomplishment of two satellites launched in 2007 and 2010 that are still operational today [21]. Twin satellites TerraSAR-X and TanDEM-X were developed by the Germany's DLR to map the elevation of the surface of the Earth. The two satellites are equipped with X band radar sensors allowing the flight systems to collect high-resolution imagery. Working in concert to collect data from different angles, the two craft are separated by 250 to 500 meters and fly in a helix orbit that combines an out of plane separation with a radial separation that ensures a low risk of collision at the orbit's poles. Since their mission start in 2010, the pair of satellites have managed to map the entirety of the Earth's surface at least twice, with some high interest areas mapped 7 or 8 times. Another mission concept along these lines that has been introduced by the French Space Agency CNES is called Pegase [22]. This mission would consist of three small satellites flying in formation at the L2 lagrangian point to observe hot giant exoplanets with the goal of determining the composition of atmospheres and their internal structures. The system would take advantage of nulling interferometry, as proposed by R. Bracewell in 1978 where destructive interference would allow the distinction of a target from its orbiting body in the infrared and visible spectrums. Two of the small craft would operate as siderostats, redirecting collected information to the central platform which acts as a beam combiner. The central system would carry the entire optical system consisting of two 40 cm telescopes as well as a star tracker for precision pointing. Should this mission be selected for further development, it would result in a great leap forward in humanity's understanding of our surroundings in the universe.

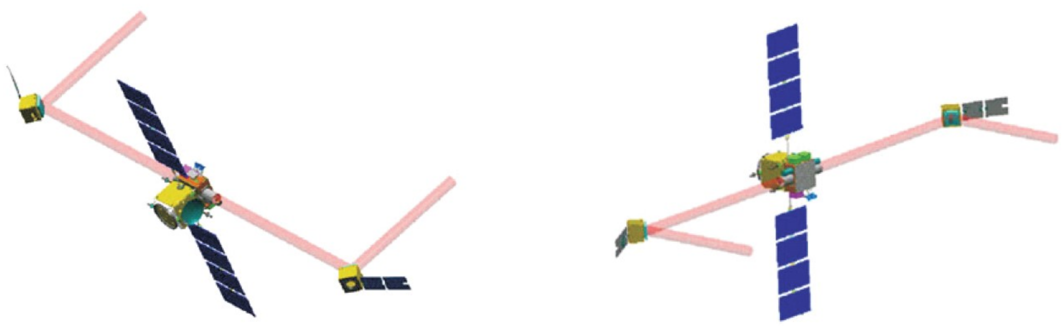

Figure 3: Pegase Configuration [22]

6 Conclusion

When applying a model-based system engineering approach to the development of complex aerospace systems, modelling and simulation are central to understanding how changes in design effect overall system performance. HSF is an open-source MBSE tool that allows users to test the viability of novel aerospace system concepts via low fidelity simulation. An example of one such novel aerospace system is that has seen great interest in recent years is that of formation flight of small satellites. The ability to collect information from locations held in relation to each other as provided by formation flight lends itself to the application of interferometry. Therefore, the objective of this thesis shall be to model a day in the life of a small satellite-based interferometer array to understand high level system requirements and identify subsystem bottlenecks.

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