Chapter 2

BACKGROUND

2.1 Survey of Undergraduate Astronomy

Existing literature on the involvement of students in the astronomical sciences suggests that the most effective means of educating new and future scientists entails the development of well-maintained and organized research teams. Research environments with students taking on apprentice-like roles, when engaged in peer mentoring and driven by compelling and achievable research objectives, have been observed to have the greatest success at retaining students in both communities of practice and wider networks of professionals [1]. Consequently, the inauguration and perpetuation of astronomy research projects, especially for students in high school and undergraduate programs, is critical to the maintenance of these communities of practice and global networks. Fitzgerald et al. [2] identified nine critical criteria to classify existing astronomical research projects as relevant in-class learning experiences for high school students:

- Capacity for original research
- Student-obtained data from research-grade instruments
- Focus on data interpretation
- Reliance on standard astronomical methodologies and approaches
- Focus on astronomical science
- Active interaction between students and educators

- Multi-teacher and/or multi-group involvement
- Appropriateness for high school educators and students
- Establishment and sustained operation

Similar criteria for success are applicable to educational research opportunities in astronomy for college undergraduate students. Reasonably-scoped research objectives in a limited-time project cycle have characterized previously successful and currently successful educational programs [3],[4]. Additionally, the acquisition of data from professionally designed and operated observation platforms and subsequent interpretation and presentation of original results has also been found to not only enhance student methodological and analytic skills; it also stimulates individual efforts by means of ensuring publication of their results in a fashion consistent with professional research methodologies and practices. This coupling of experiential learning in a true research environment with the intellectual demands and rigors of the data interpretation and publication process ensures that students gain methodological experience while also developing reasoning skill imperative to astronomical research.

While this holistic learning environment has been demonstrated to successfully train and retain new researchers in the field of astronomy, limited access to facilities and funding can inhibit research participation for students [2]. While the introduction of remote telescope systems has produced cost savings for the design and implementation of astronomical sensing systems, aggressive demand schedules for larger observatories can effectively limit the scope of student research due to proposal submission and scheduling latency. Therefore, alternative platforms, namely low-cost space-based telescopes, have been investigated for their suitability as research platforms to enable compelling research for undergraduate students. To begin the process of conceptual design for this proposed system, model-based systems engineering methodologies have been considered.

2.2 Model-Based Systems Engineering Methodologies

Several methodologies for model-based systems engineering have arisen and been surveyed in practice [5]. Many model-based systems engineering methodologies make use of SysML, a modeling language developed by the Open Modeling Group in 2007. SysML is a visual modelling language designed as an extension of the Unified Modeling Language (UML) [6], designed to overcome shortcomings of UML as a general system modeling paradigm. Many of these limitations were due to limitations in modelling requirements and parametric relationships. Modelling these relationships in SysML is less inhibited by the scope of its component elements [6]. Due to the visual nature of the models, individual models are created as diagrams with visual elements representing individual elements and relationships between elements. These diagram types can fall into one of four model categories: diagrams that model system structure, or the arrangement and interfaces of system elements and components; diagrams that model system behavior, including functions and interactions; diagrams that model requirements for the prior structures and behaviors; and parametric relationships between any element parameters or their behavior [6]. Software toolsets enabling models developed using SysML to be simulated in the Horizon Simulation Framework have been developed [7], [8]. These have some missing functionality due to the structure of the code utilized by the models, and the translator functions are unable to directly modify the underlying code as needed for the models to be properly simulated [8]. The addition of model scripting in the latest version of the Horizon Simulation Framework may prove sufficient to introduce this functionality [9], but it is not deemed an immediate necessity to introduce model generation via the translation of existing SysML models.

2.2.1 JPL State Analysis

While some methodologies are commercially-available, there are some published in open literature. One such example of a publicly-available methodology is the State Analysis methodology developed by JPL [5]. One of the principle features of the State Analysis methodology is the use of states to represent instantaneous system conditions. These system states change over time according to the models developed to describe them. Important to note, however, is that the state referred to above is an extension of the classical control theory definition of state to include system component modes, available capacity for resources, and other physical or logical parameters that can be used to totally describe a systems instantaneous state of being. The primary activities of State Analysis include: state-based behavioral modelling, state-based software design, and goal-directed operations engineering. By means of these activities, system behavior is modelled by means of system state and how its component state variables relate to one another, validation and verification strategies for generated models are detailed and organized, and system mission objectives can be characterized and modelled by means of simulation [5]. These activities can be accomplished and achieved by developing models utilizing the Horizon Simulation Framework, due to the design intent as a platform for use in conceptual design.

2.2.2 Extended Applications Beyond Conceptual Design

Such a modeling methodology lends itself particularly effectively to characterizing fault analysis when system components and states create unfavorable system conditions. To prevent such unfavorable states from arising, modelers can impose constraints on certain behaviors or parameters. This fundamentally changes the characterization of failure modes as arising from component failures to arising due to exceeded constraints on behavior or structure. As such, failure events are not directly modeled, but are prevented by designing a controller in the form of a constraint to prevent the failure from happening. [5] Subsystem failure analysis has already been studied using the Horizon Simulation Framework in previous work [10], and schedule failures are found using the built-in scheduling algorithms breadth-first search in order to identify successful schedules. Fault-tolerant designs, therefore, should include adequate constraints on system states and behaviors.

As models begin to expand over the course of project life-cycles, it may become necessary for external functionalities to be introduced to these modelling frameworks. To accomplish requirements verification, for example, may require the use of executable software to perform simulations and data analysis to verify that system requirements were satisfied. The Executable System Engineering Method developed at JPL [11] is an extension of the INCOSE OOSEM methodology [5], capable of using executable models to support requirements analysis and verification. Using these executable model results, documentation products associated with traditional systems engineering can also be supplied. This is similar in functionality to the Horizon Simulation Frameworks use of executables to run simulations and generate schedules of successful events.

2.3 CubeSat Model-Based Systems Engineering

To minimize total system cost for a space-based astronomy platform, the CubeSat specification has been primarily considered for development of space-based assets for the SSTN. [12]. MBSE methodologies for CubeSat missions and systems have been developed for numerous applications and multiple agencies and research teams.

INCOSE's Space Systems Working Group has been developing a CubeSat Reference Model using SysML [13]. The Radio Aurora Explorer CubeSat mission was selected as a reference mission the SSWG utilized in te course of developing the CubeSat modeling framework during the first two phases of development [14]. As of 2018, the CRM is in the process of being developed as an OMG specification [15], and has several packages implemented in the framework, including models of stakeholders and stakeholder needs, requirements models, use case and architecture packages, and technical measure packages for specifying system figures of merit. The CRM has also been implemented with No Magic's Cameo System Modeler, enabling models to be specified via Cameo System Modeler's graphical user interface. The CRM still has yet to be fully validated for model fidelity and function, and still requires implementation of parametric models for system mass, power, and cost at the CubeSat, subsystem, and component levels [15]. The development of robust parametric models for CubeSat systems will therefore be essential for valid model generation during the design of the SSTN. Previous work on the Horizon Simulation Framework implemented SysML model translation, successfully generating XML model files for SysML models [8], [7]. One of the modeling cases for validation was a SysML model of the ExoCube mission. However, the underlying Horizon subsystem models used by the ExoCube model files were not modified to reflect the behavior and functions specified in the SysML models, meaning the translated models could not be correctly simulated for model validation. Subsystem model modification will be required to accurately model the SSTN, but no SysML models of the SSTN have been generated. Thus, SysML model translation validation is not necessary to generate and validate a system model of the SSTN, unless an existing SysML model were to be generated.

2.3.1 CubeSat MBSE Applications

The CRM is just one of many methodologies capable of being utilized for model-based systems engineering of CubeSat systems. An MBSE framework was developed for development of the DelFFi mission [16], and utilized SysML for specification generation and requirement documentation. A parametric model was then simulated as an executable model in Simulink to validate the DelFFi system configuration and verify compliance with system requirements. This methodology is similar to what is utilized in the Horizon Simulation Framework, where requirements for subsystems can be directly specified as constraints to be satisfied during simulation. These modeling and simulation activities form a tripartite process for mission development:

1. Model Structure and Behavior Development

2. Model Architecture Development

3. Onboard Flight Software Development

Key to the MBSE methodology described [16] is the applicability of the developed models and architecture to the functional specification and development of required flight software itself. In essence, models generated for system validation can be used to form the logical and sometimes literal architecture of flight software.

Other mission developers have characterized the benefits of MBSE techniques for CubeSat mission development, such as Cipera's analysis of the ease of iterating system designs upon development of baseline models [17]. Other applications of MBSE methodologies have included conceptual design [18], multi-satellite system optimization [19], [20] and program enterprise modeling [21]. These applications range from initial concept design to high-level programmatic modeling, demonstrating the range of potential applications of MBSE methodologies in CubeSat project life cycles. It is thus imperative that the Horizon Simulation Framework not only be useful as an MBSE methodology in the early stages of SSTN system design, but it must also be capable of further development with the project life cycle to provide improved model granularity and design validation.

2.4 CubeSat and Nanosatellite Astronomy Heritage and Development

The limitations of science capabilities for nanosatellite stem primarily from instrument size constraints. Due to limitations on aperture size for smaller spacecraft, resolution and signal-to-noise capabilities are diminished by comparison with larger space-based and ground-based observatories. While design factors like deployable optics [22] and formation flight as a virtual telescope [23] can potentially augment existing small satellite astronomy capabilities, astronomical missions for nanosatellites and CubeSats presently remain limited in terms of individual instrument performance due to size constraints and other consequent design constraints. However, the advantages of nanosatellite systems compared to traditionally larger space telescopes include reduced per-unit non-recurring costs and the ability to launch and deploy multiple units as secondary payloads of launch vehicles, principally as a result of the lower launch mass per nanosatellite compared to larger spacecraft [24]. Thus, as was also noted by Cipera [17], there is the potential for alternative mission configurations, such as single spacecraft or multi-spacecraft systems, to achieve cost parity driven by the same requirements with similar overall system performance. A multi-satellite formation or constellation mission architecture must therefore be considered in the course of system design. Such "system of systems" architectures for nanosatellite space systems have been demonstrated to be feasible and effective, enabling more ambitious concepts to be developed as nanosatellite development has become more accessible and cost-effective.

2.4.1 Previous Nanosatellite Astronomy Missions

Several nanosatellite-based missions have been demonstrated to be capable of performing valuable astrophysical data collection. The BRIght Target Explorer mission (BRITE), an international collaborative mission between Austria, Canada, and Poland [25], consists of a constellation of five satellites, each satellite measuring 20 by 20 by 20 centimeters in edge length as a cubical bas. Each satellite is equipped with a 3 centimeter aperture, 24 degree field-of-view telescope for performing high-precision differential photometry on bright, low apparent magnitude stars. By operating as a constellation, individual fields of the night sky can be viewed simultaneously by all five satellites, or multiple fields can be imaged separately and concurrently. Observations of relatively luminous, high-temperature stars in the galactic plane are principal targets of interest for observation for BRITE, and research produced using data from BRITE include astroseismological studies of luminous stars, and the discovery of highly eccentric binary star systems. These results were able to be obtained from such small-aperture instruments due to the advantages of performing differential photometry from space, as opposed to utilizing a ground-based platform [26]. The scientific understanding provided by BRITE, obtained from a system of spacecraft roughly the size of an 8U CubeSat, demonstrate the compelling capabilities of nanosatellite astronomy.

More recently, the Arcsecond Space Telescope Enabling Research In Astrophysics (ASTERIA) [27] is an astronomical mission developed and operated by JPL to demonstrate the capabilities of detecting exoplanet transits using a 6U CubeSat platform. ASTERIA's fine photometric precision required for detecting exoplanet transits is enabled by its payload design, maintaining a stable payload temperature to within 0.01 Kelvin. A two-stage pointing control architecture, provided by a Blue Canyon Technologies XACT module for spacecraft attitude determination and control in addition to a two-axis piezoelectric-actuated imaging sensor, enable arcsecond-level pointing accuracy and sub-arcsecond stability for imaging operations. Precision photometry is enabled by this pointing system and allows ASTERIA to detect exoplanet transits of its three extended mission science targets: 55 Cancri, HD 219134, and Alpha Centauri [28]. Prior work in modeling attitude control systems has been accomplished using the Horizon Simulation Framework [29], though a model of sufficient fidelity for validation through simulation has not yet been successfully developed for a CubeSat spacecraft model.

2.4.2 Current Development of Nanosatellite Astronomy Missions

Recent literature by Shkolnik [30] and others anticipate a growth in the use of CubeSat systems in astronomical science missions. Due to their relatively lower development costs compared to larger astronomical space systems, CubeSat systems are well-suited for complementing the capabilities of costlier dedicated science platforms, especially time domain observations and, when utilized in constellations, enhanced target field coverage or simultaneous coverage of multiple fields. One of the major science capability gaps that has been identified to be suitable for CubeSat astronomy missions is in the performance of time domain astronomy in photometric bands normally inaccessible to ground based observatories. Some electromagnetic wavelengths are normally poorly transmitted through Earth's atmosphere, but can be detected from space in the absence of an interfering atmosphere. Proposed CubeSat missions to demonstrate astronomy capabilities at wavelengths normally undetectable by ground-based observatories include the Colorado Ultraviolet Transit Experiment and the Star-Planet Actrivity Research CubeSat. These missions are being designed to observe exoplanets in near and far ultraviolet wavelengths to complement the capabilities of other astronomical systems. Additionally, improvements in CubeSat lifetime and reliability, and recent demonstrations of optical communications and attitude control systems, have made CubeSats even more viable for astronomy instrument platforms. All these factors considered make CubeSat systems an increasingly attractive option for broad adoption and development; thus, the design and testing of robust modeling and simulation frameworks for CubeSat astronomy systems is similarly becoming more desirable and necessary.

BIBLIOGRAPHY

[1] A. Feldman, K. A. Divoll, and A. Rogan-Klyve, “Becoming researchers: The participation of undergraduate and graduate students in scientific research groups,” *Science Education*, vol. 97, no. 2, pp. 218–243, 2012.

[2] M. T. Fitzgerald, R. Hollow, L. M. Rebull, L. Danaia, and D. H. McKinnon, “A review of high school level astronomy student research projects over the last two decades,” *Publications of the Astronomical Society of Australia*, vol. 31, 2014.

[3] J. Johnson, R. Genet, J. Armstrong, G. Boyce, P. Boyce, M. Brewer, R. Buchheim, J. Carro, R. Estrada, C. Estrada, R. Freed, S. Gillette, R. Harshaw, T. Hollis, J. Kenney, S. McGaughey, C. McNab, K. Mohanan, B. Sepulveda, D. Wallace, and V. Wallen, “Astronomy Research Seminar,” *Society for Astronomical Sciences Annual Symposium*, vol. 34, pp. 139–148, May 2015.

[4] R. M. Genet, J. M. Johnson, and V. Wallen, “One-semester astronomical research seminars,” *Small Telescopes and Astronomical Research*, 2010.

[5] J. A. Estefan *et al.*, “Survey of model-based systems engineering (mbse) methodologies,” *Incose MBSE Focus Group*, vol. 25, no. 8, pp. 1–12, 2007.

[6] M. Hause *et al.*, “The sysml modelling language,” in *Fifteenth European Systems Engineering Conference*, vol. 9, pp. 1–12, Citeseer, 2006.

[7] V. K. Patel, “Sysml output interface and system-level requirement analyzer for the horizon simulation framework,” Master’s thesis, California Polytechnic State University - San Luis Obispo, Jul 2018.

[8] S. Luther, "Sysml based cubesat model design and integration with the horizon simulation framework," Master's thesis, California Polytechnic State Univerisity - San Luis Obispo, Jul 2016.

[9] M. Yost, "An iteration on the horizon simulation framework to include .net and python scripting," Master's thesis, California Polytechnic State University - San Luis Obispo, Aug 2016.

[10] I. Lunsford, "Schedule failure analysis within the horizon simulation framework," Master's thesis, California Polytechnic State University - San Luis Obispo, Jul 2016.

[11] R. Karban, F. G. Dekens, S. Herzig, M. Elaasar, and N. Jankevičius, "Creating system engineering products with executable models in a model-based engineering environment," in *Modeling, Systems Engineering, and Project Management for Astronomy VI*, vol. 9911, p. 99110B, International Society for Optics and Photonics, 2016.

[12] A. Mehrparvar, D. Pignatelli, J. Carnahan, R. Munakat, W. Lan, A. Toorian, A. Hutputanasin, and S. Lee, "Cubesat design specification rev. 13," *The CubeSat Program, Cal Poly San Luis Obispo, US*, vol. 1, p. 2, 2014.

[13] S. C. Spangelo, D. Kaslow, C. Delp, B. Cole, L. Anderson, E. Fosse, B. S. Gilbert, L. Hartman, T. Kahn, and J. Cutler, "Applying model based systems engineering (mbse) to a standard cubesat," in *Aerospace Conference, 2012 IEEE*, pp. 1–20, IEEE, 2012.

[14] D. Kaslow, L. Anderson, S. Asundi, B. Ayres, C. Iwata, B. Shiotani, and R. Thompson, "Developing and distributing a cubesat model-based system engineering (mbse) reference model," in *Proceedings of the 31st Space Symposium*, pp. 1–14, 2015.

[15] D. Kaslow, B. Ayres, P. T. Cahill, L. Hart, A. G. Levi, and C. Croney, "Developing an mbse cubesat reference model–interim status# 4," in *2018 AIAA SPACE and Astronautics Forum and Exposition*, p. 5328, 2018.

[16] J. Guo, E. Gill, and S. Figari, "Model-based systems engineering to support the development of nano-satellites," vol. 10, pp. 6991–7003, 10 2014.

[17] D. L. Cipera, "Comparison of traditional versus cubesat remote sensing: A model-based systems engineering approach," Master's thesis, Air Force Institute of Technology, 2018.

[18] M. Waseem and M. U. Sadiq, "Application of model-based systems engineering in small satellite conceptual design-a sysml approach," *IEEE Aerospace and Electronic Systems Magazine*, vol. 33, no. 4, pp. 24–34, 2018.

[19] J. Crane and L. Brownlow, "Optimization of multi-satellite systems using integrated model based system engineering (mbse) techniques," in *Systems Conference (SysCon), 2015 9th Annual IEEE International*, pp. 206–211, IEEE, 2015.

[20] A. C. Snow, J. L. Worthy III, A. den Boer, L. J. Alexander, M. J. Holzinger, and D. Spencer, "Optimization of cubesat constellations for uncued electrooptical space object detection and tracking," *Journal of Spacecraft and Rockets*, pp. 401–419, 2016.

[21] L. Anderson, B. Cole, R. Yntema, M. Bajaj, S. Spangelo, D. Kaslow, C. Lowe, E. Sudano, M. Boghosian, R. Reil, *et al.*, "Enterprise modeling for cubesats," in *Aerospace Conference, 2014 IEEE*, pp. 1–16, IEEE, 2014.

[22] N. Schwartz, D. Pearson, S. Todd, M. Milanova, W. Brzozowski, A. Vick, D. Lunney, D. MacLeod, S. Greenland, J.-F. Sauvage, *et al.*, "Laboratory

demonstration of an active optics system for high-resolution deployable cubesat," *arXiv preprint arXiv:1809.09097*, 2018.

[23] A. Naseri, R. Pirayesh, R. K. Adcock, S. J. Stochaj, N. Shah, and J. Krizmanic, "Formation flying of a two-cubesat virtual telescope in a highly elliptical orbit," in *2018 SpaceOps Conference*, p. 2633, 2018.

[24] D. Selva and D. Krejci, "A survey and assessment of the capabilities of cubesats for earth observation," *Acta Astronautica*, vol. 74, pp. 50–68, 2012.

[25] G. Handler, A. Pigulski, W. Weiss, A. Moffat, R. Kuschnig, G. Wade, G. Orleański, S. Ruciński, O. Koudelka, R. Smolec, *et al.*, "The brite-constellation nanosatellite space mission and its first scientific results," in *EPJ Web of Conferences*, vol. 160, p. 01001, EDP Sciences, 2017.

[26] K. Carroll, S. Rucinski, and R. Zee, "Arc-minute nanosatellite attitude control: Enabling technology for the brite stellar photometry mission," 2004.

[27] C. M. Pong, "On-orbit performance and operation of the attitude and pointing control subsystems on asteria," in *Proc. of the 32nd Annual AIAA/USU Conf. on Small Satellites*, 2018.

[28] M. W. Smith, A. Donner, M. Knapp, C. Pong, C. Smith, J. Luu, P. Di Pasquale, R. L. Bocchino Jr, B. Campuzano, J. Loveland, *et al.*, "On-orbit results and lessons learned from the asteria space telescope mission," in *Proceedings of the AIAA/USU Conference on Small Satellites, The Year in Review, SSC18-I-08. http://digitalcommons. usu. edu/smallsat/2018/all2018/08*, 2018.

[29] S. M. MacLean, "Modeling and simulation of a sounding rocket active stabilization system," Master's thesis, California Polytechnic State University - San Luis Obipso, 2017.

[30] E. L. Shkolnik, "On the verge of an astronomy cubesat revolution," *Nature Astronomy*, vol. 2, no. 5, p. 374, 2018.