University of Colorado
Department of Aerospace Engineering Sciences
ASEN 4018

Project Definition Document (PDD)

Collision Avoidance System Testbed (CAST)

Approvals

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1.1. Project Customers

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2. Problem or Need

Our space is cluttered! Currently there are over 500,000 objects[1] in orbit the size of a marble or larger, and new objects are being added with every launch. At orbital velocities, these objects pose a serious threat to other objects, and collisions can be disastrous, potentially adding thousands more objects. Opportunities for destruction, collection, or restructuring of this debris often requires solutions that could be weaponized, and, subsequently, are in contention with the Outer Space Treaty[2] (along with having many other issues). It is therefore advantageous that active objects are capable of detecting and avoiding collisions.

The Collision Avoidance System Testbed (CAST) project will develop a test environment representative of a satellite collision scenario. The project will also develop a hardware package to validate the functionality of the test environment. The hardware package will consist of a sensor system, avoidance software, and maneuvering hardware. That will detect and track nearby objects at risk of collision. Using data from the sensors, the software will determine the action the spacecraft must take. Any current laws, regulations, and procedures will be considered during the development of the software design (or requirements).

The test environment will be a 2D physical model. The velocities and time scales of the test bed will be scaled down from their orbital magnitudes in order to ease manufacturing and observability of the test. The validity of the physical model will be checked using 3D and 2D simulations. Possible collision scenarios which could be modeled on the test bed include cross track collisions, as well as head on and overtaking collisions.

Through this project, valuable insight will be gained into the viability of a real-time spacecraft avoidance system. Further improvements can be made based on test and simulation results of the system. Benefits and drawbacks of the collision avoidance package will be identified and will serve as a basis for future developments with the ultimate goal of creating a package fit for use on spacecraft.

3. Previous Work

This project delves into an issue that has come about numerous times in the course of technological innovation: that of how to regulate a new realm of navigation. Maritime regulations were needed as more ships navigated the open seas, road regulations were needed as cars became a common sight on urban streets, and aircraft regulations became necessary as air travel gained frequency, and now sights are turning to navigation in the space domain.

Previous physical experimental work regarding interactions in the space domain have yet to yield substantial industry standards. Sensor-package solutions relevant to collision avoidance have been developed in the past, however comprehensive integration for this tracking and avoidance problem has not been established. Despite the lack of much concrete automated collision tracking and avoidance testing, there are several theoretical models and related projects that reach valuable conclusions relevant to this project's design process.

For example, one MIT study in 2002 developed a primarily 2D (3D-adaptable) theoretical solution to collision avoidance using Mixed Integer Linear Programs (MILPs)[3]. Due to the unique characteristics of a space environment, linear modelling is highly representative of real collision situations; the main limitation of this approach is the computational costs of MILPs. Fortunately, this complication's impact can be limited through the use of optimization softwares that rely on heuristics for increasing computational efficiency (the study used CPLEX[3]).

While there are clear differences between spacecraft formation flying and collision avoidance, many factors are shared between the two projects. One undertaking at Narvic University College attempted to address collision avoidance in formation flying by utilizing a Null Space Based (NSB) Model, which focuses on velocity vectors and Jacobian matrices to create a model much more applicable to 3D environments[4]. This model was initially adapted from systems used on marine vessels and mobile robots[4]. The resultant translation from the marine and ground transportation technologies in this study is an encouraging one, and likely a common logical connection that we will rely on.

Both NSB and MILPs are regularly used in attitude and trajectory models, which makes another field of space collision avoidance relevant to this project: rendezvous and spacecraft docking. Challenges with this mission set differ from general launch collision avoidance due to the low-proximity and low-velocity nature of docking, but use of similar models and ranges of sensing technologies make this field of exploration another great resource for gaining insight into this project[5].

Over the course of the past decades, highly capable and robust ground-based tracking systems (such as the US Space Surveillance Network, SSN) have been developed by numerous nations, providing the means to track objects orbiting earth with reliability and accuracy. Historically, this database has been used to assist a human operator in navigating spacecraft safely through Earth's cosmic neighborhood, but this method imposes significant work and stress on the operator. No work has been previously done on potentially integrating ground-based tracking systems into automated collision detection and avoidance.

4. Specific Objectives

The CAST project will deliver a representative testing environment and baseline sensor/movement package for testing of collision avoidance software. 2D and 3D simulations of selected collision scenarios will be created in order to quantify error of adapting a testing environment for orbital collisions in 2D. This process will serve as a baseline for future development and investigation of other collision scenarios.

The following table outlines the levels of success for the critical project elements. Level 1 indicates the minimum requirements for the project to be considered a success. Levels 2 and 3 indicate further functionality that are driven by the customers' desires. Level 4 indicates the ideal state of the project, and is the end goal for the team and customer. Higher level objectives also satisfy all lower level objectives under the same project element (for example, meeting a level 4 requirement also satisfies levels 3, 2, and 1).

Project Element	Level 1	Level 2	Level 3	Level 4
Simulation/ Model	2D simulation of test environment. 3D simulation of realistic spacecraft collision scenario.	Simulation based error quantification of mapping 3D collision to 2D testing environment.	2D and 3D simulation of single collision scenario with detect and react procedures implemented.	N/A
Testing	Testing environment designed and built.	Stationary testing of sensor hardware and maneuvering system within testing environment.	Full systems testing occurs with objects moving below velocity representative of prescribed collision scenario.	Full systems testing occurs with relative motion between the avoidance package and colliding object at full representative velocities.
Test Environment Software	Software is capable of receiving sensor data and indicating that data has been received.	Software is able to find the range to secondary objects in the testbed.	Predict trajectory of secondary objects on test bed. Software determines whether or not to activate the maneuvering system in order to avoid collision.	Object detected in adequate time to avoid collision. Determination is made as to whether collision avoidance is appropriate. If appropriate, the maneuvering system is activated to avoid collision and return to a stable state.
Test	Sensor hardware selected	Sensor hardware capable	Sensor hardware capable	N/A

Environment Sensor Hardware	and integrated into the avoiding object. Sensor hardware capable of (yes/no) detection of objects on the testbed.	of (yes/no) detection of objects above TBD view angle with TBD surface finish.	of tracking objects in sufficient time to avoid collision.	
Test Environment Maneuvering Hardware	Maneuvering system hardware selected and integrated to control the avoiding object.	N/A	Maneuvering system provides the capacity to avoid collision within selected scenario.	Maneuvering system allows for repeatability, predictability, and consistent (measureable) movement force.

5. High Level Functional Requirements

5.1 Functional Requirements

The following are the high-level, guiding functional requirements for the Fall 2020 and Spring 2021 project scope:

1.1 A 3-dimensional orbital collision scenario shall be reduced to a 2-dimensional simulation with the associated collision parameters replicated in a test bed where the body is restricted to 2-dimensions

1.1.1 The test bed shall support representative collision scenarios that preserve the time scale (ratio of distance to relative velocity) and optical view angle (ratio of cross section diameter to distance) of the orbital scenario.

1.2 The test system shall be capable of detecting incoming objects (active or inactive) in a representative collision scenario on the test bed.

1.2.1 The test system shall be capable of quantifying relative motion through position and velocity measurements.

1.3 The test system shall be capable of avoiding a collision in a representative collision scenario without the test system technology performance levels exceeding those of current, full-scale spacecraft hardware

It is important for this system to have the ability to detect incoming objects, as the first step in a collision avoidance scenario is to identify the threat. Although, it is important to limit the scope of object detection in the chosen sensors since too broad of a sensing scope will provide a flood of information due to the vast amount of space debris present in LEO and GEO. It is also necessary to quantify relative motion of incoming objects to both use as a determining factor in whether a collision is imminent, as well as determining the required avoidance maneuver. A 2-dimensional test will be designed to test the functionality of the collision avoidance system. Identifying the level of success of the physical test bed will be possible by comparing the test results to a simulation of the true, full-scale collision scenario. This simulational model will also aid in the development of the test bed through the appropriate scaling factors of position, velocity, and orbit-adjusting forces.

The development of a custom sensor suite to be integrated in future satellites is outside of the scope of this senior project. Specifically, the purpose of this project is to develop a test bed capable of detecting incoming objects, quantifying relative motion, and determining the appropriate collision avoidance actions using a guidance algorithm. Future work can be performed on improving a recommended sensor suite for collision detection, as a primary goal of this project is to represent and implement a common collision scenario in a 2-dimensional test environment.

5.2 CONOPS

The deliverables for this project are part of a multi-year mission to design a collision avoidance system to use in space. The concept of operations for the larger multi-year mission is shown below in figure 1. The larger mission consists of three phases: detecting a potential collision, a maneuver determination and orbit change implementation, and lastly a collision avoidance confirmation. The change in orbit will be initiated by thrusters onboard the spacecraft and the avoidance maneuver will be in three dimensions which allows for a larger selection of avoidance courses. The collision avoidance system will be capable of performing the maneuver independent of the communication systems on board the object it is on the path to collide with.

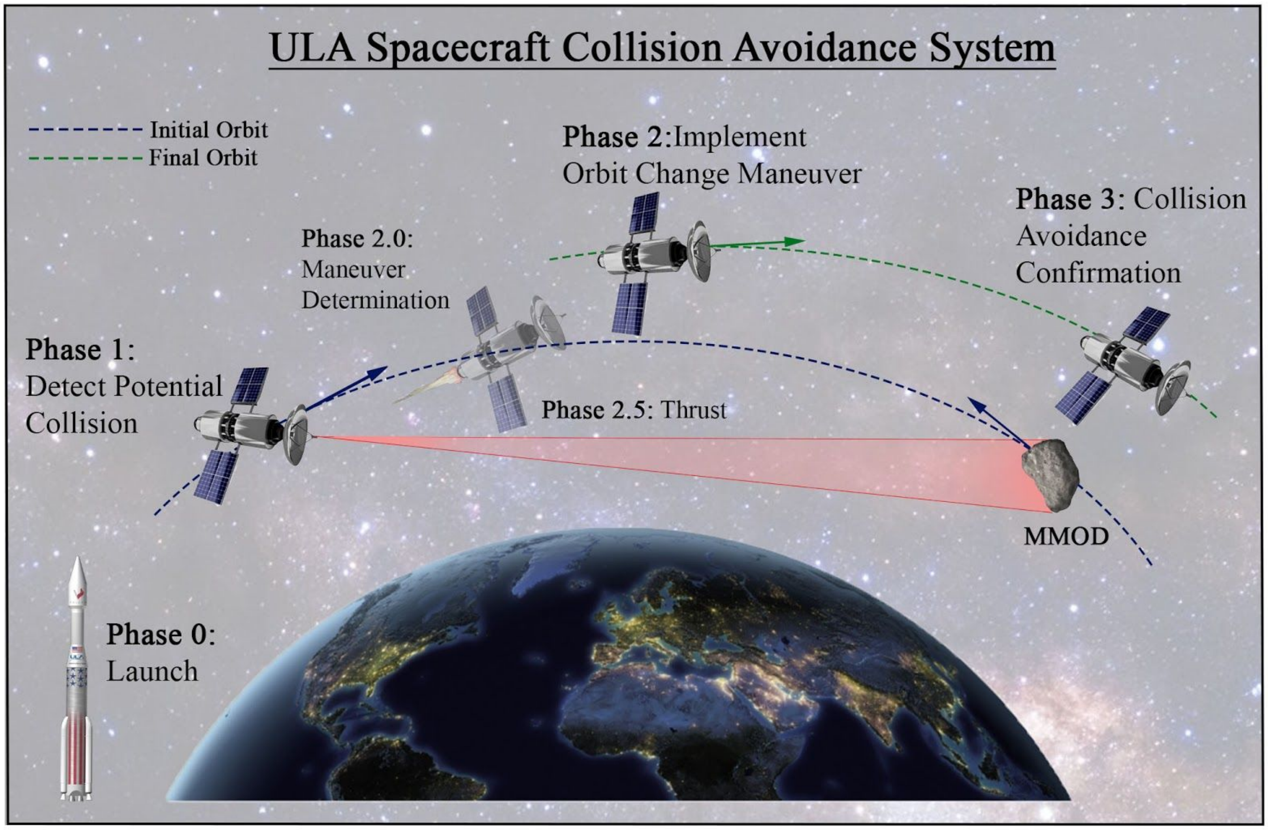

Figure 1: CONOPS for larger mission

The concept of operations for the Fall 2020 and Spring 2021 semesters shown in figure 2 are more closely focused on developing a test-bed and collision avoidance system for collision scenarios. The test would model a three dimensional collision avoidance scenario in two dimensions on a frictionless test bed. A sensor onboard the device will first sense an object and then the algorithm will predict the object's trajectory which will dictate the avoidance maneuver it will make. The test system will then implement the maneuver using a new force vector to make the device follow a new path that does not collide with the object. After moving on the new path it will be manually verified that the device did not collide with the object on the new path. The two dimensional results will then be compared to the two dimensional simulation of the same collision.

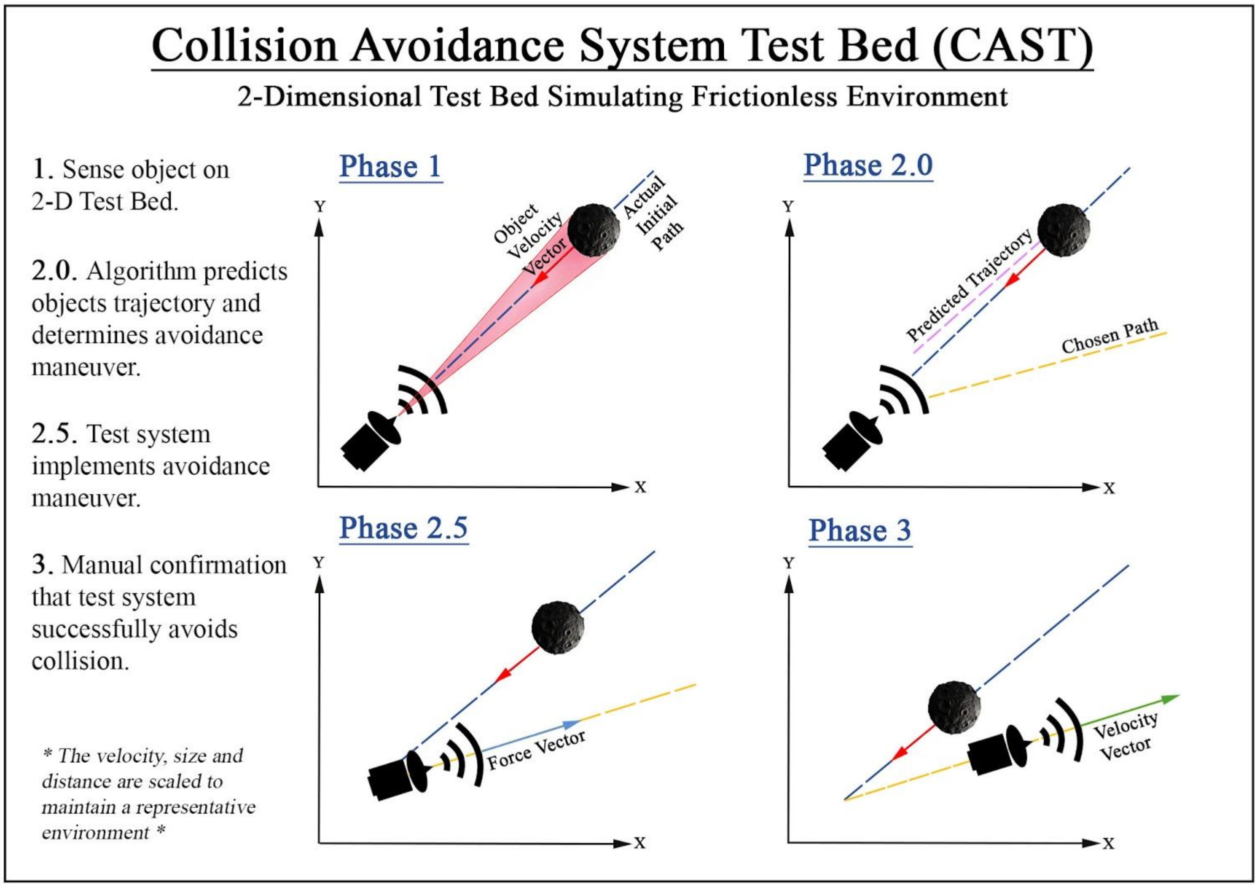

Figure 2: CONOPS for smaller mission

6. Critical Project Elements

1. Simulation and Validation

Elements of the collision detection, determination, and avoidance software deployed in the 2D test environment shall be tested in a simulated 3D space scenario. This simulated scenario shall be representative of a potential real-world application of the completed product. The simulation shall validate whether the techniques used in the 2D test can be applied to an operating spacecraft and produce desirable results. Potential areas of improvement and further development will also be identified using this simulation.

2. Testing

A test which is representative of real-world collision avoidance in the space environment is a critical element for this project. The test shall be performed on a 2D plane and will demonstrate the effectiveness of the collision detection and avoidance system.

A test chassis shall be built containing all hardware elements of the avoidance system. This will include sensing hardware, processors, and a reaction system. This chassis will undergo a variety of tests wherein it interacts with an additional object that has a relative velocity.

Discrepancies between the representative test and a simulated implementation in three-dimensional space will be characterized and quantified.

3. Sensing Hardware

The 2D demonstration test chassis shall include sensing hardware capable of detecting local objects. Data gathered from the sensing hardware must be adequate for collision determination and avoidance decisions. Without appropriate sensing capabilities, the 2D test will not be able to demonstrate successful collision avoidance methods.

4. Maneuvering Hardware
Hardware for test chassis maneuvering must be acquired and/or constructed. Such hardware is essential for validating the sensing hardware and software package in physical tests. This hardware must be capable of providing control to the test chassis and shall be representative of a real-world spacecraft maneuvering.

5. 2D Collision Determination Software
Using data gathered from the test object's sensing hardware, a software must be implemented to assess the likelihood of a collision. If an object is deemed a threat for future impact, the collision determination software must also be capable of predicting critical aspects of the future collision (e.g. time and location of impact).

6. 2D Collision Avoidance Software
Software shall be developed with the ability to assess an imminent collision on the testbed and, if appropriate, respond with a maneuver to avoid the collision. Demonstration of this avoidance software will be performed on a 2D scaled test, and a theoretical application of this software will also be tested in a simulated 3D space environment.

7. Financial and Management
The project will stay within the constraints of the given budget ($5000) and will maintain an organized inventory of purchases, available funds, and planned spending.

8. Examine Transition from 3D Simulation to 2D Test
Evaluate losses in realism defined by the 2D test environment compared to the 3D simulation.

7. Team Skills and Interests

Describe the areas of expertise and/or interests of the team members on your project, and relate them to the critical project elements identified above.

Critical Project Elements	Team Member	Associated Skills	Interests
2, 3, 6	Adam Holdridge	*Mechanical Design* - SolidWorks, Manufacturing, *Coding* - MATLAB, Control Systems, STK	Mechanical Design, Propulsion, Systems, Research, Manufacturing
2, 3, 5, 6	Angel Hoffman	*Coding* - MATLAB, C++, Cubesat flight software (projects class), sensing software (projects class) *Simulation* - MATLAB, STK *Construction* - Solidworks, manufacturing composites *Testing* - cubesat sensor testing	Software development, research, controls & autonomous systems, manufacturing, propulsion
4, 5, 6, 7	Cameron Turman	*Coding* - MatLab, VBA, Python, Coded Micrometeoroid Analysis Tools (LM) *Testing* - Micrometeoroid tests (LM), Systems Testing (Projects Class) *Construction* - Woodworking, Solidworks, Assembly	Software development, mechanical design, research, mathematical modeling

		Logistics - Organizational Leadership (AFROTC), Secretarial Work, Inventory Management (LM)	
1, 4, 5, 6, 8	Conner Martin	CAD, 3D printing, thermal and structural analysis, MATLAB, Python, C/C++	Software development, mathematical modeling, control systems, autonomous systems
1, 5, 6, 8	Griffin Van Anne	*Coding* - MATLB, Python, C++,(CSCI minor) *Software* - flight software testing and validation(internship)	Autonomous systems, simulation, software development, controls
1, 5, 6, 7	Hugo Stetz	MATLAB, C++, Python (CSCI minor) Organizational leadership, inventory management (NROTC) Prediction, simulation, and comparison (ASEN 2012 TA)	Software development (simulation, verification, data analysis and organization), organization and logistics, research, astrodynamics and physics
1, 3, 5, 6	Isaac Goldner	*Testing/Mechanical Design/CAD* - cold gas reaction control system (CUSRL) *Systems Engineering* - vehicle systems internship *Software* - MATLAB, C++ (CSCI minor)	Mechanical design, propulsion systems, systems engineering, software development
1, 4, 6	Jason Balke	MATLAB, Python, C++, STK	Astrodynamics, simulation, software development, control systems
1, 4, 5, 6	Reade Warner	MATLAB, C++, STK, Astrodynamics	Software development, control systems, astrodynamics modeling/simulation
1,2,4,6	Roland Bailey	Manufacturing CNC and lathe, MATLAB, STK, Physics	Manufacturing, Propulsion, Collision avoidance software
1, 6, 7	Sam Hartman	*Simulation:* MATLAB Modeling and Simulation *Construction:* Manufacturing *Logistics:* Organizational Leadership and Planning	Manufacturing, Hardware, Electronics, Modeling
1, 4, 5, 6, 8	Trace Valade	Matlab, Python, C++, (CSCI Minor) Cubesat Flight Software (Work at LASP), Machine Learning (Operations Research), Control Systems, Mathematical Modeling, (APPM Major) Simulation, Robotics (Club Team Lead ~2 years)	Software, Controls, Autonomous Systems, Physics Modeling and Simulation

8. Resources

Critical Project Elements	**Resource/Source**
Fabrication/manufacturing	Matt Rhode: expert in mechanical design and manufacturing Machine shop: AERO machine shop gives access to mills, lathes, CNC, and various other tools for manufacturing

Sensor Selection/Design	Dr. Jade Morton: PAB Member, expert in remote sensing and instrument design.
Astrodynamics	Dr. Marcus Holzinger
Testbed	PILOT Frictionless Table (initial)
Electronics	Trudy Schwartz: Microelectronics
State Estimation	Dr. Nisar Ahmed
Collision Assessment	Captain Austin Sellers

9. References

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[3] Richards, A., Schouwenaars, T., How, J. P., and Feron, E., "Spacecraft Trajectory Planning with Avoidance Constraints Using Mixed-Integer Linear Programming," *Journal of Guidance, Control, and Dynamics*, vol. 25, 2002, pp. 755–764.

[4] Schlanbusch, R., Kristiansen, R., and Nicklasson, P. J., "Spacecraft formation reconfiguration with collision avoidance," *Automatica* Available: https://www.sciencedirect.com/science/article/pii/S0005109811001154?casa_token=xD9koQXzYfUAAAAA:92mT3hwWR2oIkwdyvhj9ZltnYxyUH_xgAsDEF5gMPCzoUH9tFwMhasIQKYQl5aV76COFFWTmKAI.

[5] Singla, P., Subbarao, K., and Junkins, J. L., "Adaptive Output Feedback Control for Spacecraft Rendezvous and Docking Under Measurement Uncertainty," *Journal of Guidance, Control, and Dynamics*, vol. 29, 2006, pp. 892–902.

[6] "Automating collision avoidance," *Phys.org* Available: https://phys.org/news/2019-10-automating-collision.html.

10. Appendix

The Three Phases of Collision Avoidance: Prior research also provides context for the scope of the collision avoidance problem by splitting solutions into three phases (collision avoidance, plume impingement, and final configuration selection). This project will primarily focus on collision avoidance, but the multi-year nature of the final endeavor will likely need to establish the other factors thoroughly.

Machine Learning Collision Avoidance: Collision avoidance is an industry-wide investigation into machine learning. Although machine learning models are extremely complex, and likely beyond the capacity of what a year-long project with little prior heritage can explore, it is important to note that the approach is an avenue that many Aerospace interests, such as ESA[6], are heavily investing in. Consequently, it is possible, if not probable, that this project takes up this direction in future years.

History of Collision Avoidance: The 17th century marked nations' first forays into the realm of naval law, as rulers and leaders sought to agree on who could sail where. However, it wasn't until the mid-1900s that the worldwide community started to look seriously into international regulations that could be used as the "law of the sea." As wealth and technology spread across the world in the decades after World War II, more and more ships flying innumerable national and corporate flags were filling the oceans, and it became more and more imperative to have an established rulebook so that seagoing vessels could navigate safely amidst each other. This culminated in the United Nations Convention on Law of the Sea (UNCLOS), which established rules for how ships should navigate open waters.

A similar development occurred when cars first started appearing on streets. At first, there were no rules to govern them, since many thought that cars would be luxury items and would never become an important part of life. As cars became faster and more dangerous and more of them filled the streets, however, it became imperative to start creating rules for how they were to safely navigate. Likewise, planes were initially an unregulated, private affair, but as more planes filled the sky it became clear that rules needed to be made so that pilots did not harm themselves or others.

Now, a new frontier has opened for human navigation: space. It has been over 60 years since Sputnik was launched into space as the first satellite in orbit, but it is only fairly recently that space has been accessible to private companies and smaller nations, and not just a handful of global superpowers. The need has arisen for developing a system by which space vessels can safely navigate our orbit. And this need is made more complicated by the fact that much of what fills Earth’s night sky is unresponsive debris rather than communicative vessels.