University of Colorado - Boulder

Department of Aerospace Engineering Sciences

ASEN 4018 - Senior Projects 1: Design Synthesis

Collision Avoidance System Testbed (CAST)

Conceptual Design Document

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I. Information

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Contents

Nomenclature

CAST	Collision Avoidance System Testbed
CONOPS	Concept of Operations
CPE	Critical Project Element
FR	Functional Requirement
DR	Design Requirement
MTI Radar	The Moving Target Indication Radar
FMCW Radar	Frequency Modulated Continuous Wave Radar
LRF	Laser Rangefinder
LiDAR	Light Detection and Ranging
SOCRATES	Satellite Orbital Conjunction Reports Assessing Threatening Encounters in Space
LEO	Low Earth Orbit
GEO	Geosynchronous orbit

II. Project Description and Objectives

A. Project Purpose and Description

Our space is cluttered! Currently there are over 500,000 objects 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 spacecraft, and collisions can be disastrous, potentially adding more debris. It is therefore advantageous that active objects are capable of detecting and avoiding collisions on orbit. The main objective of this project is to develop a 2-dimensional testbed that demonstrates that a potential collision can be avoided. While the long term goal of this project is to implement such technology on spacecraft, it is not yet necessary that components chosen for the testbed would be used on a real spacecraft as long as the capabilities of these chosen technologies do not exceed the capabilities of technologies currently available on state of the art spacecraft.

In order to achieve the main objective, the Collision Avoidance System Testbed (CAST) project will develop a 2-dimensional model of a 3-dimensional collision scenario. This model will inform the team on how a physical 2D test environment shall be developed in a way that is representative of the chosen satellite collision scenario. The developed testbed must scale many parameters to preserve the time to collision for the real 3D scenario in the 2D test. In order to demonstrate collision avoidance capabilities, the testbed must be capable of sensing an incoming object, determining whether it is a threat, and maneuvering if it is necessary. Therefore the testbed must include a hardware package to validate the functionality of the test environment and demonstrate that the avoidance capabilities of the developed test system could possibly be extended to use on real spacecraft. The hardware package will consist of a sensor system that will detect and track nearby objects at risk of collision, avoidance software that will determine if a maneuver must be made and and how it should be executed, and maneuvering hardware. The validity of the physical model will be checked using 3D and 2D simulations.

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.

B. Specific Objectives

As stated above, the main objective of this project is to develop a 2-dimensional testbed capable of demonstrating that a potential collision can be avoided. This involves relating a 3D collision scenario to a representative 2D testbed, sensing a potential colliding object, determining the necessary reaction, and maneuvering if necessary. In order to meet this main objective, several requirements must be met (outlined later in this document). Table 1 outlines the levels of success for the project. Level 1 indicates the minimum requirements for the project to be considered a success. Level 2 indicates further functionality driven by the customers' desires. Level 3 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.

C. Concept of Operations

The deliverable for this project is the first 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 or the possible end product 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. The full, multi year mission overview CONOPS is shown in Figure 1.

Table 1 Levels of Success

Project Element	Level 1	Level 2	Level 3
Simulation	Simulation relates 3D collision scenario to motion in a 2D plane while maintaining important/relevant collision parameters	N/A	Simulation relates 3D collision scenario to motion in a 2D plane while maintaining all important/relevant collision parameters that can realistically be implemented in the integrated test environment
Integrated Test Environment	N/A	Integrated test environment fully translates 2D simulation to a representative/scaled 2D physical scenario that is capable of verifying some critical project elements	Integrated test environment verifies all CPEs, control laws, and is capable of avoiding a detected colliding object
Evaluation	Test system detects object on possible collision path	Test system detects object on possible collision path and provides a maneuver plan to avoid collision	Test system detects object on possible collision path and maneuvers to avoid collision. Test results are verified by comparison to the 2D simulation

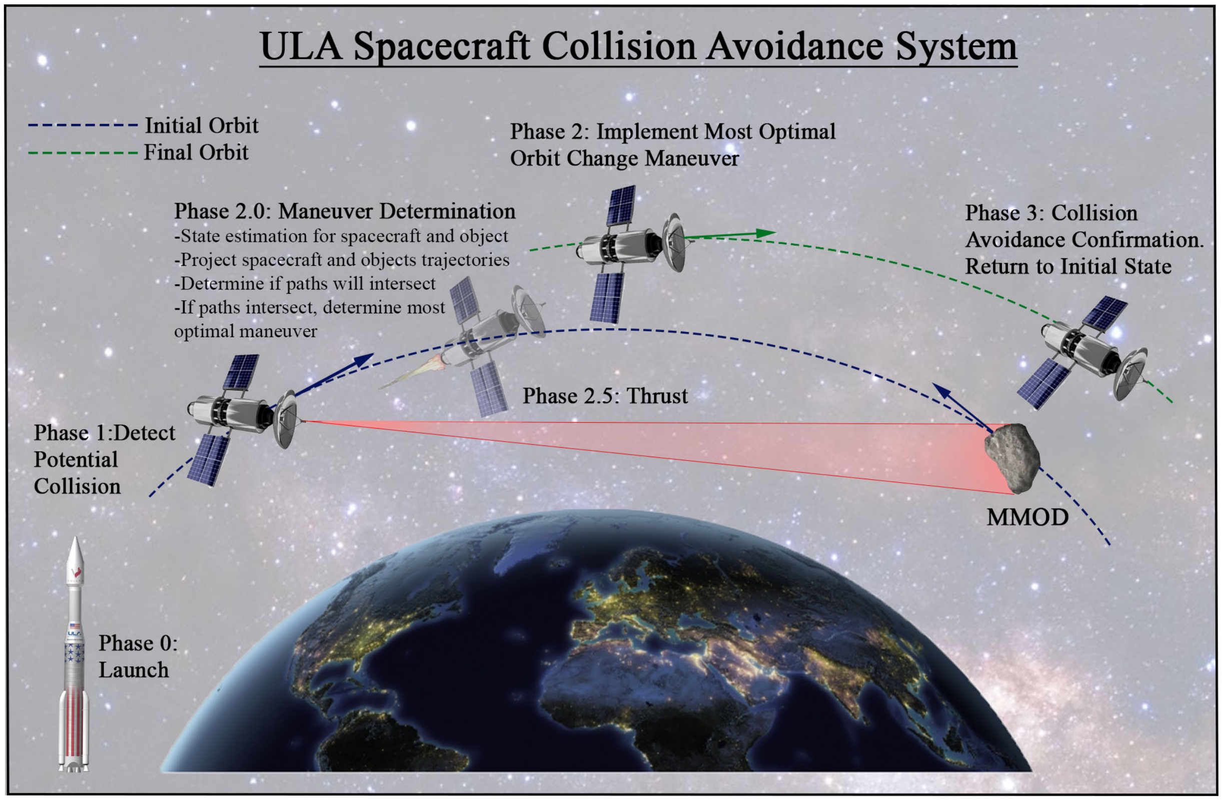
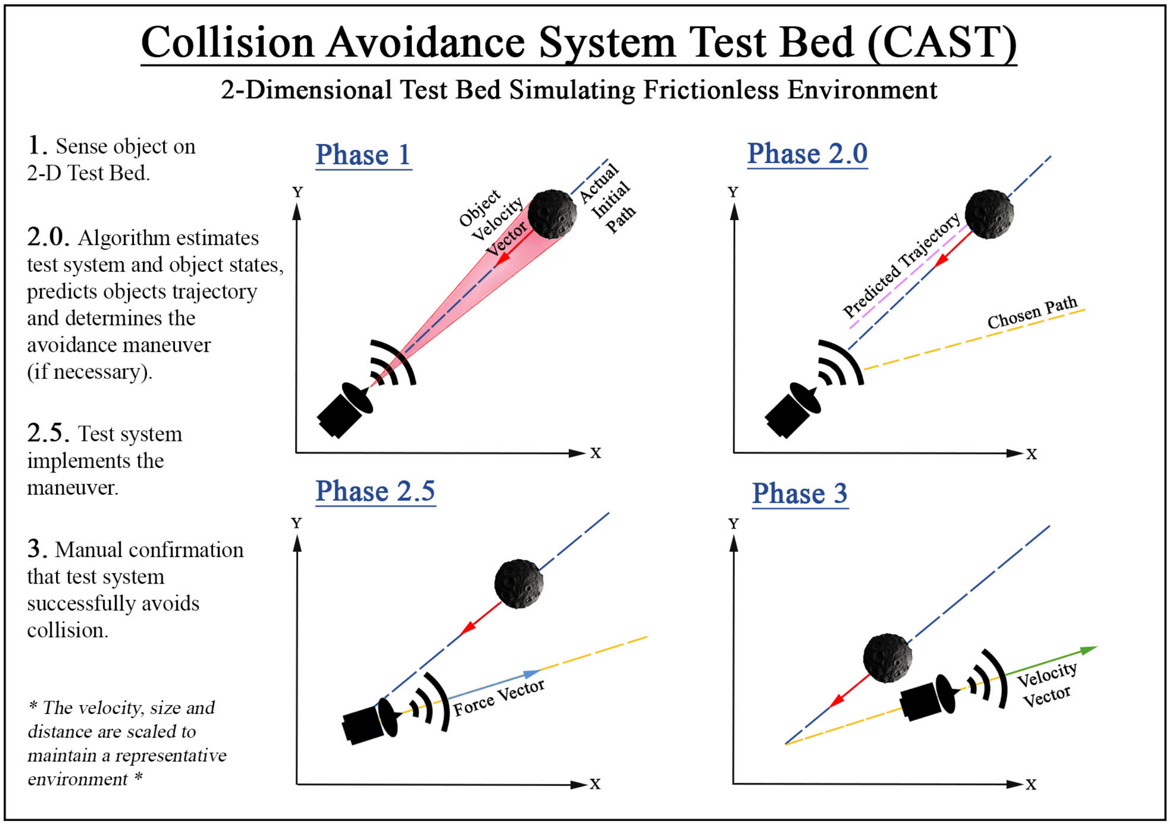


Figure 1 Mission Overview CONOPS

The concept of operations for the Fall 2020 and Spring 2021 semesters shown in figure 2 are more closely focused on determining whether the end product is feasible for real spacecraft by developing a test-bed and collision avoidance system for a collision scenario. The test would model a 3D collision avoidance scenario in 2D on a test bed. A sensor onboard the device will first sense an object. Then the algorithm will predict the object's trajectory, dictating whether an avoidance maneuver must be performed. The test system will then implement a chosen maneuver by applying a force vector, changing the velocity and making the device follow a new path that does not collide with the object. After moving on the new path it will be qualitatively verified that the device did not collide with the object. The 2D results will then be compared to the 2D simulation of the same collision to verify the validity of the test.



Collision Avoidance System Test Bed (CAST)

2-Dimensional Test Bed Simulating Frictionless Environment

1. Sense object on 2-D Test Bed.

2.0. Algorithm estimates test system and object states, predicts objects trajectory and determines the avoidance maneuver (if necessary).

2.5. Test system implements the maneuver.

3. Manual confirmation that test system successfully avoids collision.

** The velocity, size and distance are scaled to maintain a representative environment **

Figure 2 2D CONOPS

D. Functional Block Diagram

The functional block diagram for the CAST project is shown in figure 3 below. There are eight sections within the project: 2D simulation, inputs, launching module, sensing/data capture, micro controller and command module, outputs, reaction, and verification. The diagram shows the process between all of the sections and the more detailed interactions within each section.

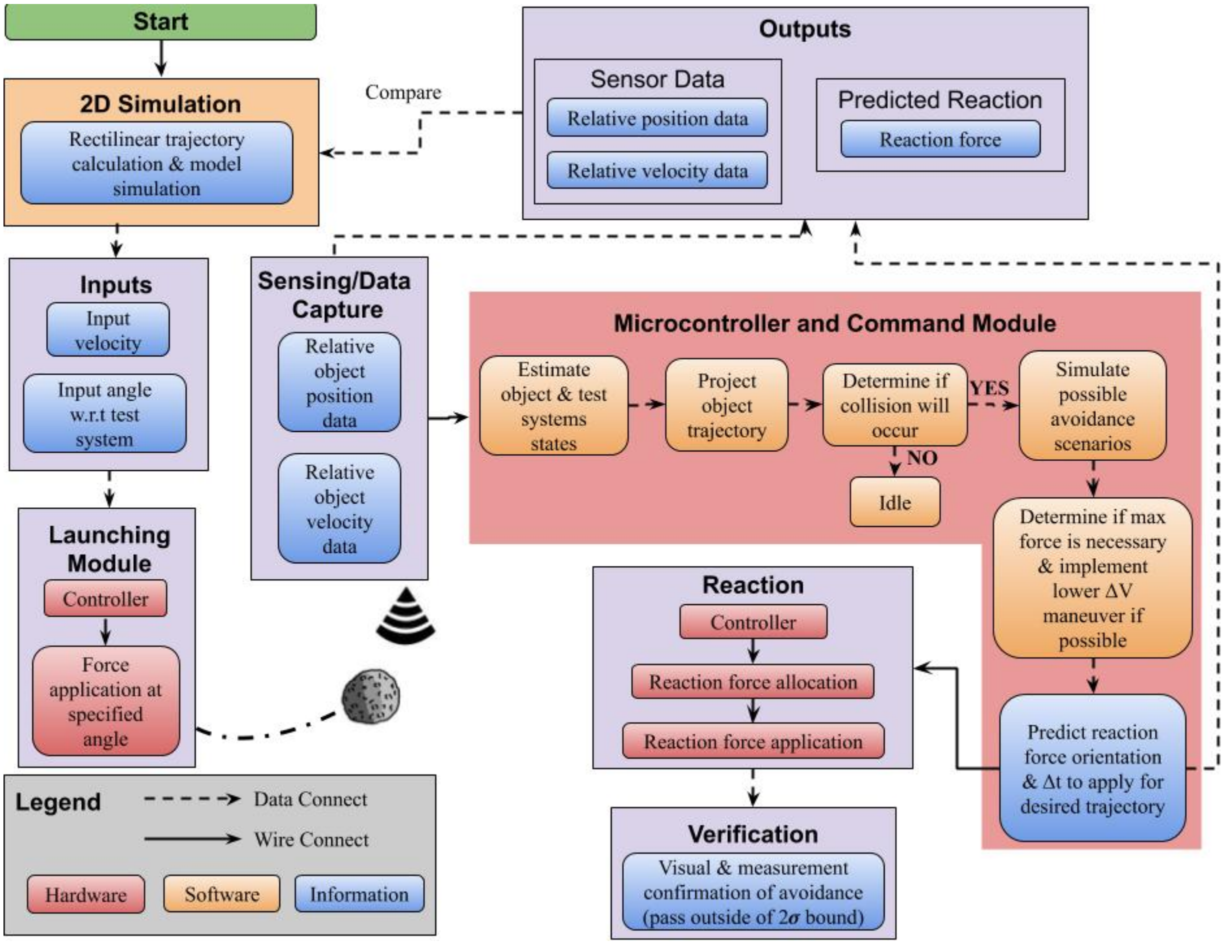


Figure 3 Functional Block Diagram

E. Functional Requirements

The following functional requirements describe necessary capabilities of CAST and are motivated by the project purpose and objectives. By defining what CAST must be capable of, the functional requirements allow for the consideration of any and all design options. Design options are considered and studied later in this document.

FR1 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 bodies are restricted to 2-dimensions.

FR2 The test system shall be capable of detecting incoming objects (active or inactive) in a representative collision scenario on the test bed.

FR3 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.

III. Design Requirements

FR 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

Motivation: Space is becoming increasingly cluttered with active satellites and inactive orbital debris. There are numerous types of collisions including head-on collisions, overtaking collisions, and anything in between. The goal of this project is to replicate a common orbital collision scenario to advise on a required response to avoid collision. A two-dimensional test bed will simulate this collision and associated avoidance maneuver. Therefore, complex, three-dimensional orbital collision trajectories are reduced to two-dimensions in a simulation. This simulation will guide and verify the accuracy of the two-dimensional test bed representation of the orbital collision scenario. Typically the hardware will be used to verify a simulation, although in the case of this project the simulation is verifying the hardware and ensuring it is a representative relative motion environment.

DR 1.1 The test bed shall support representative collision scenarios that preserve a time scale (ratio of distance to relative velocity) up to 100-150 seconds (LEO) and/or 1600 seconds (GEO).

Motivation: The magnitude of orbital velocities (LEO or GEO) are infeasible to model on a one-to-one scale with a test bed. Additionally, the magnitude of orbital relative positions required for sufficient time to avoid a collision are also infeasible to model on a one-to-one scale with a test bed. Therefore, the ratio of distance to velocity results in a time scale where both distance and relative velocity can be reduced while preserving the orbital scenario.
Verification: The time scale of a full-scale orbital collision scenario will be computed by $t = \frac{D}{V_{rel}}$ from the two-dimensional simulation, where "t" is time, "D" is distance, and "V_{rel}" is relative velocity. The two-dimensional test bed time scale will be computed with the same relation. The DR1.1 will be met if the time scale of the test bed is lower than that of the full scale. In other words, the time scale of the full two-dimensional simulation is the upper bound for the time scale.

DR 1.2 The test bed shall support representative collision scenarios that preserve an optical view angle (ratio of cross section diameter to distance) of 0.226-0.29 (LEO) and/or 0.05 (GEO) arcseconds at the furthest point

Motivation: The size of the object being detected is important in addition to the distance between the center of gravity of each object in the orbital collision. For example, sensing the same size object at 1 km versus 10 m is much different in terms of sensor requirements. The sensor's view angle of the object must be defined so as to scale object sizing in the representative test bed. While the goal of this project is not to create a sensor package for use on satellites, this project is meant to establish a replicative environment where future work can be performed in this area.
Verification: The optical view angle of a full-scale orbital collision scenario will be computed by $\theta = \frac{D_C}{d}$ from the two-dimensional simulation, where "θ" is the view angle, "D_C" is the cross-sectional diameter, and "d" is the distance between the two objects. The two-dimensional testbed view angle will be computed with the same relation. The DR1.2 will be met if the view angle of the test bed is less than that of the full two-dimensional simulation

DR 1.3 The lower bound of the time scale shall be 10 seconds.

Motivation: The lower bound of the time scale (upper bound defined in DR1.1) is defined based on the proper scaling of force from a full-scale satellite to the replicated test environment. A 3U cubesat weighs approximately 6kg and commonly incorporates Hall Effect thrusters with a maximum thrust of 50mN. Therefore, it takes approximately 6.33 seconds to translate 1 meter for such a cubesat under ideal conditions. Thus a time scale of 10 seconds is assumed to account for transients such as pointing, startup, and/or off-nominal thrust values.
Verification: The design requirement will be met if the computed timescale of the test environment is greater than 10 seconds.

DR 1.4 The test bed shall be capable of repeatedly creating a relative velocity with less than 2.5% deviation from the scaled, test bed relative velocity.

Motivation: Modeling an orbital collision scenario with various cross-track angles results in different relative velocities. Therefore, an acceptable error bound for the relative velocities can be established by computing the percent change in relative velocity from a 1° deviation in cross-track angle of 800km LEO orbits. By taking the average of these percent change values of relative velocities, an acceptable error of 2.5% is established.
Verification: This design requirement will be met and verified through testing if the test bed relative velocity deviation from the scaled value computed by the two-dimensional simulation is less than 2.5%.

DR 1.5 When modeling an orbital scenario with a collision trajectory the test system shall create a collision with 95% (2σ) success.

Motivation: As the goal of this project is to model a collision avoidance system it is imperative to have the ability to repeat a test where the modelled trajectory is consistently a collision trajectory. Part of the design trade space involves the distance between the two colliding objects and the relative velocity between them. Since the distance between the objects will be defined as part of the trade study, defining an acceptable error for the relative velocity vector would be arbitrary. Therefore, to define an important design requirement revolves around the necessity of a test bed collision no matter the distance between objects on the test bed.
Verification: This design requirement will be met and verified through testing and observation if the incoming object makes contact with the maneuvering object when a collision trajectory is being modeled. As part of subsystem integration, the maneuvering hardware for the collision object will be tested through a minimum of 20 iterations to ensure that a collision scenario can consistently be created.

DR 1.6 The test system shall implement a detect and react procedure.

Motivation: This requirement defines the fundamental process of the final test system product. The test system will be successful if onboard sensors are used to detect an incoming object on a collision trajectory and use this information to inform a decision on whether/how to maneuver.
Verification: This design requirement will be met through testing and observation. During testing the data recorded by onboard sensors will be stored, along with the decision logic for the subsequent maneuver implementation. If the sensor data is used to inform an avoidance maneuver, or recognize the need for no avoidance maneuver, this design requirement will be met.

DR 1.6.1 The test system software shall receive sensor data about an incoming object, including relative velocity and position.

Motivation: An integrated test bed product will require the use of sensors to supply information about an external object on a collision trajectory and be capable of integrating this data into the collision avoidance software.
Verification: This design requirement will be met and verified through testing if onboard sensor(s) transfer measured position and velocity data to the avoidance software algorithm.

DR 1.7 The test system shall be fully functional after repeated detect and react procedures, where full functionality is defined as the ability to sense position and velocity data for an incoming object, integrate this data into the avoidance algorithm software, and perform an avoidance maneuver.

Motivation: The final test bed product, in addition to future work, will be used to improve understanding appropriate responses to collision scenarios. To continually refine and improve these reactions it is necessary that a single test bed system be capable of repeated use for this response refinement.
Verification: This design requirement will be met and verified through testing if multiple (a minimum of 3) collision scenarios are implemented on the test bed where the sensors collect required data, inform the software algorithm, and implement an avoidance maneuver.

DR 1.8 The total cost of the test bed system shall be less than $5000.

Motivation: The project funding established by the customer and through ASEN 4018 is limited to $5000.
Verification: The total cost of all components associated with CAST development will be recorded and upon completing the final test bed product the expenses will be totalled. If the total cost is less than $5000 this design requirement will be met.

FR 2 The test system shall be capable of detecting incoming objects (active or inactive) in a representative collision scenario.

Motivation: The test bed system must be able to detect incoming objects, as the first step of an avoidance maneuver is recognizing a collision threat. Not only must the collision avoidance system detect an incoming object, but it also must predict the future trajectory of the object.

DR 2.1 The test system shall be capable of making at least two position and relative velocity measurements in sufficient time to avoid collision.

Motivation: In order to predict the trajectory of the incoming object, two sets of position and velocity measurements must be obtained. The trajectory of the incoming object can be determined from these two measurements since the collision trajectory will be near-rectilinear at this point.
Verification: If the test bed successfully records at least two sets of position and relative velocity measurements this design requirement will be satisfied.

DR 2.2 The test system shall sense the time scale (defined in DR1.1) with an uncertainty less than 0.2 seconds.

Motivation: A 3U cubesat weighs approximately 6kg and commonly incorporate Hall Effect thrusters with a maximum thrust of 50mN. Therefore, it takes approximately 6.33 seconds to translate 1 meter for such a cubesat. Thus, a time scale of 10s is assumed to account for transients such as pointing, startup, or off-nominal thrust values. A 0.2s time scale corresponds to an uncertainty of 2%, which is a common uncertainty limit observed in engineering systems.
Verification: The true position and velocity of the incoming object will be measured to compute the true time scale and will be compared to the sensor recorded values. If the difference between the true and measured time scales are less than 0.2 seconds, then this design requirement is satisfied.

DR 2.3 In order for the test system to sense an incoming object, a reorientation maneuver shall not be required.

Motivation: Reorientation of the test system is not required to detect an incoming object, as it is assumed that the spacecraft is pointing such that detection of the incoming object is already possible. Therefore, the type of collision is defined primarily by the relative velocity of objects
Verification: This design requirement will be satisfied if the test bed system successfully detects all incoming objects in each test scenario without needing to change the pointing angle of the sensor.

FR 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.

Motivation: One of the main goals of this project is to develop a representative environment of an orbital collision in order to model an avoidance maneuver. After sensing an incoming object and determining it is a threat, the test bed will simulate an avoidance maneuver with the required forces to move the test bed. Due to the scaling involved in this project, it is important that the relative scaled force applied in the avoidance maneuver does not exceed that of a full-scale satellite.

DR 3.1 The test system shall generate sufficient force to avoid a collision with the covariance ellipse of the sensor package.

Motivation: The test bed system must not only avoid where the object is thought to be, but also where the object may be due to the sensor error.
Verification: The error of the chosen sensor suite for the collision avoidance system will be specified by the sensor data sheet. Using this value, the estimated error of the sensor will be used to model an ellipse around the incoming object which must also be avoided to successfully avert a collision. With the covariance ellipse shape defined by sensor error, this design requirement will be met if during the physical test the incoming object is avoided in addition to the potential error around the object.

DR 3.2 The first course of action in an avoidance maneuver shall not be to apply the largest capable force in the direction perpendicular to the relative velocity

Motivation: While successfully avoiding the incoming object is critical to this project, it is also important to consider the delta-V required for a particular maneuver. The cost of a maneuver in space (delta-V) is a critical consideration for in-space maneuvering as limited propellant resources are available on spacecraft. Although, in some orbital collision scenarios it may be necessary to apply the largest capable force in the direction perpendicular to the relative motion velocity to successfully avoid a collision.
Verification: This design requirement will be met if the avoidance algorithm incorporates logic to determine if maximum force in the direction perpendicular to relative velocity is necessary. If it is not, a

lower cost maneuver will be implemented. The associated logic with this decision shall be stored for a particular test to confirm this design requirement is met.

IV. Key Design Options Considered

The key design options for this project include the collision scenario analyzed, the testing environment, the maneuvering hardware for both the spacecraft object and colliding object, and the sensor package used. Each of these design options will be explored through both research and trade studies in order to select the most appropriate options for a baseline design.

A. Collision Scenario

The chosen collision scenario will have significant implications for the scope of CAST. The project will be most valuable if a common collision scenario is chosen to model. However, all collision scenarios have unique characteristics that will influence the size and other important characteristics of the chosen physical 2D testbed. Consequently, the feasibility of developing a testbed for each collision scenario must be studied. In addition to considering the test environment implications, the likelihood of real-world occurrence for each scenario is also assessed. There are two primary factors to consider for the collision scenario - the first of which is the altitude in which the conjunction occurs. Collisions in altitudes of low earth orbit (LEO), higher altitudes of LEO, and collisions at geosynchronous orbit (GEO). The second consideration is the angle at which the collisions occur. The angle of the collision effects both the relative velocity of the collision and the amount of time in which the objects are within line of sight. Collision were divided into head on collisions ($135° < \theta \leq 180°$), cross track collisions ($45° < \theta \leq 135°$), and overtaking collisions $0° < \theta \leq 45°$(Overtaking).

1. Low Altitude LEO Collisions

Orbits in LEO are typically in the range of 400km to 2000km altitude[1]. LEO is very crowded compared to other orbital ranges, particularly in the range of 700km to 1000km[2]. Due to the high traffic, spacecraft in LEO are most at risk for collision with other spacecraft as well as debris. For this reason, focusing on a conjunction in the LEO range promises to be very applicable to a real-world collision avoidance scenario.

Within LEO there is still a large range of potential collision parameters. Figure 4 displays the influence of conjunction angle on the relative velocity of two colliding objects in LEO. The relative velocity increases dramatically as the collision angle increases from 0° to 180°. In order to narrow the scope of each collision scenario, two ranges of LEO collisions have been defined with low altitude orbits being those below 800 km and high altitude being those above 800 km. Objects below 800 km in orbit experience the highest orbital velocities, while also experiencing the most drag.

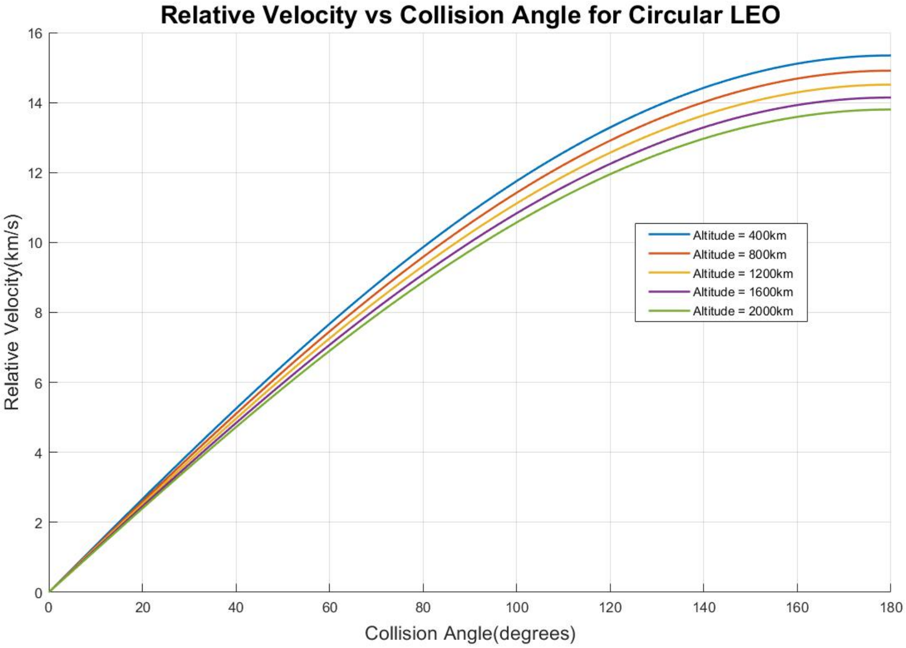


Figure 4 This figure shows the relative velocity of two objects colliding in LEO for various collision angles

Pros	Cons
High concentration of objects	Largest relative velocities will result in a larger test bed
Test bed designed for high relative velocities will be able to simulate other scenarios	

2. High Altitude LEO Collisions

While collisions at higher altitudes of LEO have many similarities to their lower altitude counterparts, there are a few factors which warrant distinction between the two. The most important of which is the impact of debris in these orbits. While objects in lower orbits may decay within a few years, objects in higher orbits above 800 km require decades to decay [3]. This longer decay time means that collisions at higher altitudes will will have a significantly greater impact on future satellites and they will be a hazard for longer than their low altitude counterparts.

Pros	Cons
Relative motion is approximately linear	Less common than many other scenarios
Slowest relative velocities	

3. GEO Collision

Another orbit with a high concentration of satellites is the geostationary orbit at 35,786 km in altitude. This orbit, especially the geostationary belt at 0° inclination is highly desired because the orbital period matches the rotation speed of the earth. This has resulted in a very crowded environment in this orbit. Debris in geosynchronous orbit presents some unique challenges. Due to the orbit altitude, the time of orbital decay is thousands of years. Perturbations due to the earths gravity cause the objects in this type of orbit to drift towards longitudes of 75° and 255°. Outside forces such as gravitational effects from the moon and sun also cause the inclination of geostationary satellites to fluctuate between 0° and 15° every 55 years [4]. Observations of objects at GEO are more difficult due to the altitude, and observations by the Space Surveillance Network occur less often. Due to the higher orbit, objects in GEO will collide at smaller relative velocities than similar scenarios in LEO. This allows for an easier creation of a physical test environment however if the test environment is limited to only replicate GEO speeds then it will not be able to be applied to many LEO scenarios.

Pros	Cons
Lower relative velocities will result in smaller test bed	Low velocity test bed not adaptable to other scenarios
Avoidance system more beneficial due to untracked objects in GEO	Less common than many other scenarios
Avoidance prevents debris from remaining in orbit for 1000s of years	

4. Overtaking Collision:

Another important consideration is the angle at which a collision takes place. The collision angle has a great impact on the relative velocity of the collision, as well as the debris field formed after the collision. The probability of each conjunction type was evaluated using Satellite Orbital Conjunction Reports Assessing Threatening Encounters in Space (SOCRATES) created by CelesTrak, which evaluates conjunctions and publishes a list of the most likely to occur[5]. Figure 5 shows the distribution of conjunction angles for 20 of the most likely collision scenarios for the week of 09/20/2020.

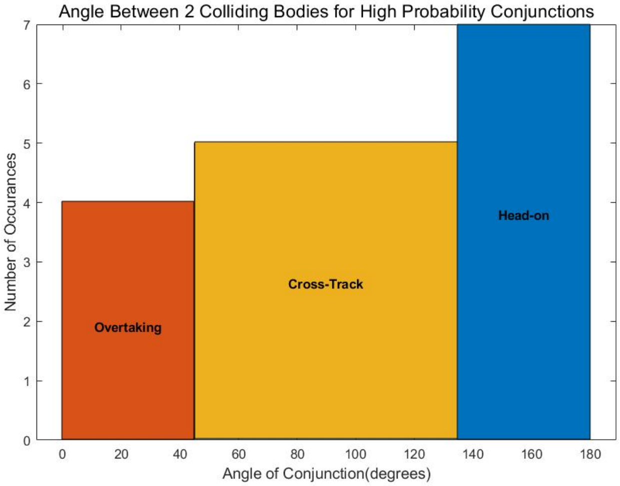


Figure 5 This figure shows the distribution of collision angles for 20 high probability conjunctions

An overtaking collision has a conjunction angle of less than 45° between the two colliding objects. This means the resulting relative velocity magnitude is less than the individual velocity magnitude of either object. Such a collision allows a detect and avoid system more time to respond to an approaching object than either the head-on or cross-track collision. This is a desirable characteristic for CAST because it reduces difficulties in scaling collision velocities to a 2D test environment. Figure 6 shows a potential overtaking collision between two satellites.

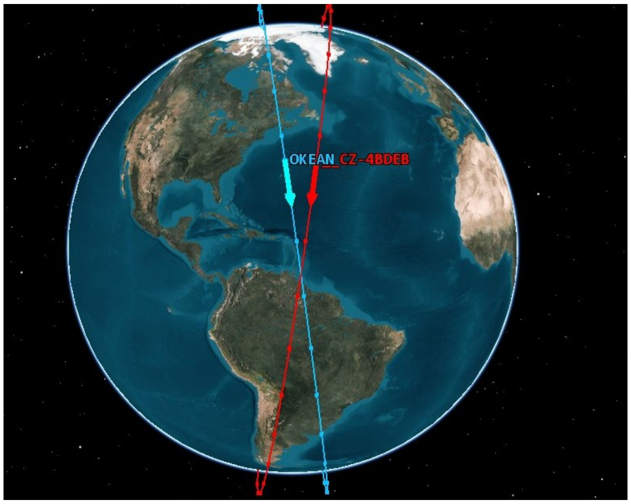
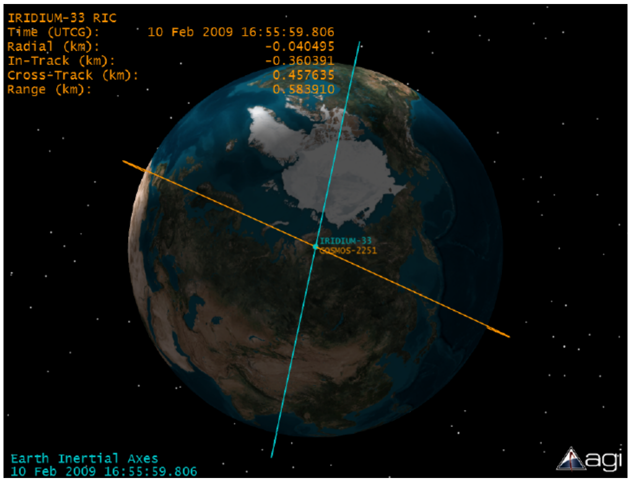


Figure 6 This figure shows a LEO conjunction that was deemed high probability by SOCRATES

Pros	Cons
Relative motion is approximately linear	Less common than many other scenarios
Slowest relative velocities	
Minimal effect of altitude on relative velocity	
Total FOV requirement is less than other scenarios	

5. Cross-track Collision:

A cross-track collision has been defined as a collision with a conjunction angle between 45° and 135°. The relative velocities between the two objects involved in this collision have a wide range as an impact can be made in many different ways. In 2009, the US-built Iridium 33 satellite collided with an inactive Russian satellite at an altitude of 800km. The collision occurred at a near right angle with a relative speed of roughly 10km/s[6]. This incident was the first high-velocity collision between two satellites, and serves as a very important historical reminder of the importance of developing an avoidance system, particularly for the Cross-track scenario.



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IRIDIUM-33 RIC
Time (UTCG):      10 Feb 2009 16:55:59.806
Radial (km):                     -0.040495
In-Track (km):                   -0.360391
Cross-Track (km):                 0.457635
Range (km):                       0.583910
```

Figure 7 This figure shows a simulated view of the 2009 satellite collision between Iridium 33 and Cosmos 2251. Note the near right angle intersection between the two orbits

Pros	Cons
Frequently Occurring	High relative velocities
Large amount of available data	Extreme variety in possible scenarios
Historical precedent available from 2009 collision	

6. Head-on Collision:

The final collision scenario considered is head-on. A head-on collision has been defined as a conjunction between two objects at greater than 135°. When this occurs, components of the individual velocity vectors combine and result in a large relative velocity magnitude. With the amount of energy in Head-on collisions, an avoidance system would help avoid a catastrophic impact from occurring. These high relative velocities do make an avoidance system much more difficult than the other scenarios due to the quick detect and respond time required.

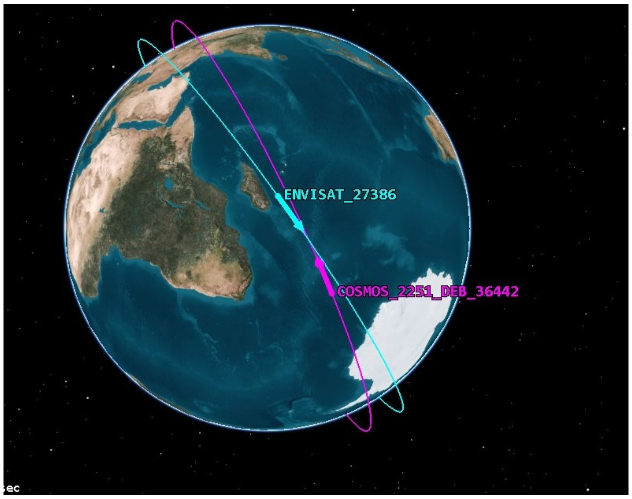

Figure 8 This figure shows a LEO conjunction that was deemed high probability by SOCRATES

Pros	Cons
Relative motion is approximately linear	Highest relative velocities will likely require large test setup
Frequently Occurring	

B. Testing Environment

As the main deliverable of this project, the testing environment is of utmost importance. The test environment must be created such that it is representative of the relative velocities, distances, and time characteristics of the chosen collision scenario. The chosen test environment will determine the level to which the test is representative of the space collision environment. Creating a representative environment will be a challenge due to the non-rectilinear motion of objects in orbit, the frictionless space environment, and the large scales involved in on-orbit collisions. While the test environment is restricted to 2D, there are many possible solutions that must be considered, some options were proposed by the customer, some came from research, some from experts in the field of aerospace, and others came from creative problem solving and critical thinking. Another consideration is that the chosen test environment may dictate the hardware that can be used for the testbed. The physical limitations of these environments will also limit what sorts of collision situations we are able to represent. Consequently, figure 9 offers good context for what distances we will need to construct in order to represent desired velocities and distances while varying time and scaled object size. They use the standard average diameter of a metal BB as a benchmark for the size of the collision object, and demonstrate that representing increased velocities or time require larger test sizes.

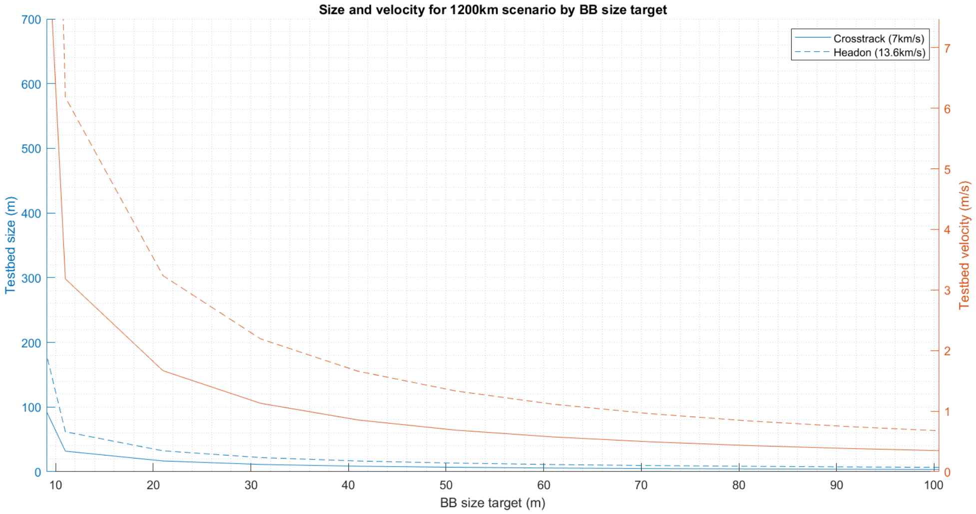

Figure 9 Testbed size and velocity to represent a collision at with a 10 second reaction time with varying BB size scale.

1. Air Table

This physical setting was the one initially mentioned by the customer in their presentation, however the domain of options is not restricted to this option. It is essentially a much more precise version of an air hockey table. These tables utilize a grid of small holes connected to a higher pressure air source. The higher pressure causes a steady flow rate of air through all of the holes. "Puck" devices or devices with large surface areas can "float" on these types of tables due to the lift that the rising air causes on the holes, as shown in Fig 10. They key benefit from having these pucks float on a cushion of air is that they see very little frictional force as the friction encountered is the drag of the puck through the air. These table are usually expensive, on the order of half of our budget, for a high quality one. The Aerospace Department at CU already owns one of these tables as it was used in a previous senior project meaning that access to one would be free.

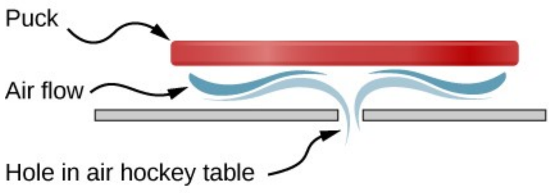

Figure 10 Puck on an Air table

On an air table multiple methodologies for maneuvering can be used. As is with most of the low friction physical settings, one of the best options is to utilize a single maneuverable test vehicle on the air table and fire projectiles such as BB's at it. One of the biggest limiting factors for the air table is its size and cost. In our case cost is not an issue but size may be. Orbital velocities are very high and accurately representing them on a ground based test also requires relatively large velocities. At such velocities a small test environment would run out of room very quickly and would likely not give the necessary freedom to maneuver. This is especially pronounced when looking at alternate maneuvering methods such as having both vehicles moving at the same time. If both objects involved in the collision are moving much more space is needed to allow the test to occur. It is also important to note that these tables are fragile and having potentially fast impacts on the surface could damage or even ruin the table.

Pros	Cons
Initial idea envisioned by customer	Heavily limited size
Multiple maneuvering options	Easily damaged
One table currently available for free	Difficult to upgrade scale for future
Low friction	Limited design adaptability
Easily transportable	Only relative specifications currently known
High-speed capable [7]	

2. Linear Rails

This physical setting involves a large apparatus constructed of linear rails powered by motors. Mounting the "spacecraft" on one of the rails will enable it to quickly and accurately produce 1 dimensional motion. Then, mounting this first rail on a parallel set of synchronized rails will enable the full system to output 2 dimensional motion whose main limitations are the capacity of the motors and the durability of the rails themselves. The approximate layout of the proposed linear rail system is shown in Figures 11 and 12.

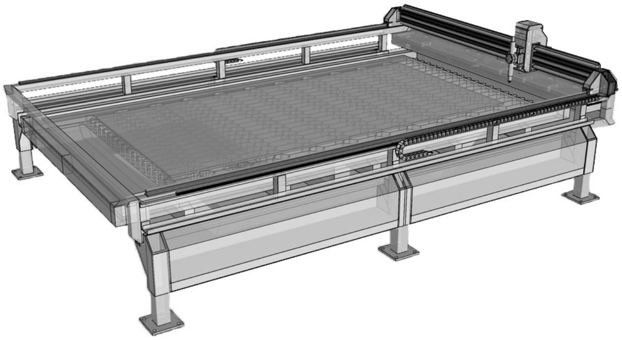

Figure 11 Linear rail system

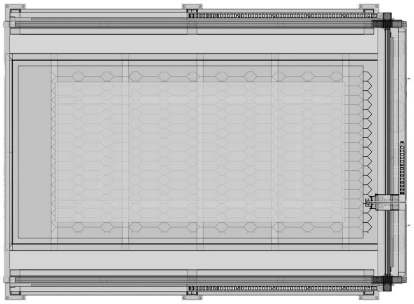

Figure 12 Linear rail system—top view

This system draws much inspiration from small scale control systems like 3D printers and CNC machines that have 2 and 3 dimensional capabilities. Linear rails have the advantage of being low friction, fairly easy to construct, and capable of handling speeds up to 9 m/s[8]. Moreover, this system of linear rails could easily be driven by a variety of maneuvering hardware options. On the other hand, linear rails have the potential to be one of the most expensive environment options, and require a fundamental understanding of construction and integration of hardware. Given the high potential velocities of the test scenario, there is also potential risk of an improperly constructed system or incorrect maneuvering input to be of a magnitude to damage the system, which could be both a safety risk and a major impact on the project budget.

Pros	Cons
Prior heritage of system for testing collisions	Relatively expensive [9]
Medium speed capable	Advanced construction required
Flexible sizing	Limited mobility of test system
Flexible material options	Potential to break itself
Potential to combine with other environments	
Relatively flexible design adaptability	
Multiple maneuvering options	

3. Teflon Sheet

This physical setting consists of a large, flat, and level surface being covered seamlessly with sheets of Teflon material to create a reduced friction environment that a self propelled or externally driven object could utilize to achieve higher speeds and motion more akin to a space environment. Teflon provides very low static and dynamic coefficients of friction when interacting both with itself and metals such as steel. Teflon is more technically known as Polytetrafluoroethylene or PTFE. It is a material that is used often times to coat cook-wear as it is hydrophobic and highly temperature resistant. The hydrophobic nature of PTFE comes from its very high electronegativity. This high electronegativity is exactly what gives PTFE its low friction properties. Friction partly depends on the interaction of the Van der Waals forces between two materials and with high electronegativity PTFE hardly has any Van der Waals forces.

PTFE may seem like an exotic material but it has become very mainstream. As mentioned it is used heavily in cooking applications but sheets of Teflon are also used in many aerospace applications. It can be obtained in multiple forms but for our application the primary ones are a pure sheet of PTFE and a sheet of some other material coated in PTFE. PTFE is not the easiest material to make so pure sheets of PTFE can often be expensive. The best option for our group and our price point would be to go with something like a fiberglass sheet coated in PTFE. Sheets like this often cost around $70- $100 for 5 square meters. This means the group could obtain a sheet with enough area to perform large scale tests for relatively cheap. The Teflon sheets also provide excellent flexibility with location of testing in the COVID environment. Essentially, any large flat area could be used for a backing to the Teflon sheets such a tennis courts or basketball courts. The CU rec center courts could be either rented or used for this purpose or even local courts close to group members.

One slight concern for the use of PTFE is how well it will continue to provide low friction with high velocities and potentially large masses. As speed increases so does energy and this can cause the PTFE to be less effective. This is often quantified in material properties by the quantity of PV limit or pressure velocity limit[10]. Expressed in units of feet per minute times pound per inch squared, the PV limit describes either how fast your object can move, how heavy it can be, or a combination of both. For PTFE sheets this PV limit lies around 2,500. In order then to achieve high velocities it will be important to make sure the test vehicle is relatively light weight.

Pros	**Cons**
Multiple maneuvering options	Collision object control uncertain
Flexible sizing	Set-up and take-down for each separate test occasion
Durable and reusable	Potential to damage some ground environments
High speed capable [11]	Potential for need of reserved facilities
Potential to combine with other environments	

4. Open Air

This physical setting involves using the vast open air environment to simulate desired collision scenarios. The biggest advantage of performing collisions tests in this environment is the theoretically unlimited amount of space that can be utilized to simulate the collision. Additionally, high air speeds are distinctly more achievable for conventional (preconstructed) vehicles than high ground speeds. These are major advantages that are highly applicable to the variables that we want to control, however employing the open air environment for this test is accompanied with several challenges. Not only does this environment require the use of flight capable vehicles and projectiles, but operating in the air enforces aerodynamic limitations. Creating an entirely airborne test environment imposes additional baseline technological and aerodynamic competencies on our team that would otherwise be much less relevant to the overall scope of the project. Finally, all of these advanced factors combining will make it difficult to limit the 3D environment or the open air to the required and simpler 2D test.

Pros	**Cons**
Theoretically unlimited size	Very expensive
High-speed capable	Limited design adaptability
Easily adaptable for future of the experiment	Collision object control uncertain
	Fragile and difficult to replace
	Functionality limited to aerodynamic capability
	High baseline technology or physics competency required
	Difficult to limit to 2 dimensions

5. Ice Rink

This physical setting consists of an ice rink being utilized to create a reduced friction environment that a self propelled or externally driven object could utilize to achieve higher speeds and motion more akin to a space environment. The primary obstacle faced by this environment is availability for testing. Although CU has an available ice rink that is free to reserve for students, the time slots are fairly limited, and the administrative load for reserving, cleaning, and dealing with changing COVID regulations will present a significant challenge to the team [12].

Pros	**Cons**
Low friction environment	Facility reservations required
Relatively large size	Prolonged exposure to freezing environment
Multiple maneuvering choices	Limited design adaptability
High-speed capable [13]	Potential for extensive clean up before and in between tests
Potential to combine with other environments	

C. Maneuvering Hardware

In order to ultimately demonstrate that a colliding object can be avoided, the developed test apparatus must be able to move. This requires some sort of hardware that can exert a force on the apparatus in a particular direction. It is important to choose the maneuvering hardware such that it does not exceed the realistic capabilities of most spacecraft. Most maneuvering hardware used on the 2D physical test environment will likely exceed the capabilities of technologies used on real spacecraft at orbital scales but the chosen maneuvering hardware can be artificially limited with software to ensure that the test is still valuable and still a sufficient representative test environment. This requires that the induced acceleration be similar to the magnitudes of acceleration that can be induced by propulsion systems or thrusters on real spacecraft. In addition to the avoiding package moving, the incoming object must also move in order to create a collision. This requires largely the same research as the maneuvering hardware, but such hardware must be evaluated in a different manner. While the maneuvering hardware for the spacecraft object only needs the ability to move to avoid the colliding object, the maneuvering hardware for the collision object must be able to move the colliding object long distances at relatively high velocities. Again, it is not necessary that the maneuvering hardware is chosen to be similar to what would be used on orbit due to the inherent differences between the physical 2D test and the actual space environment. This allows for the consideration of many different design solutions. The type of hardware used to maneuver in the testing environment is dependent on what testing environment is used. As most proposed environments are low friction, relevant options include combinations of one free moving vehicle with ballistic objects shot at it or two fast freely moving vehicles. Each of these two setups feature their own strengths and weaknesses.

Having a single moving test vehicle with objects shot at it allow the test area to be relatively small as the avoiding vehicle only needs to move out of the way of the object fired at it. This setup also allows for more off the shelf components to potentially be used for the firing apparatus. Ideas include using BB guns, or other styles of pneumatic launchers. BB guns are devices that often mimic real guns at much slower velocities and masses. Projectiles from BB guns are called BB's and they usually weigh 12 grams with a 6mm diameter. These BB's are fired up to velocities of 1.5 $\frac{m}{s}$ by compressing air in a cylinder and using that air pressure to accelerate the BB. Depending on what size of object is needed for the test, this concept could also be scaled up towards larger styles like a potato gun. With any option safety is going to have to be a large priority. Objects will be moving at high rates of speed in these tests in order to make them representative so the group will have to take precautions to avoid injury and damage.

Multiple mobile autonomous test vehicles allows for a larger range of testable scenarios and more adaptability and flexibility in the future. This option, however, greatly increases cost and complexity. Multiple moving vehicles also means that the test area would have to be much larger. This is because each vehicle has to move at the relativistic speeds for the duration of the test. In practice this may mean that this method is impractical as all the methods proposed for low friction environments scale cost with area. This style of testing would have more adaptability to future projects and would present more options for the type of collisions that can be tested. The decision to go with multiple moving vehicles versus a single moving vehicle will be made based on feasibility. In any case the following maneuvering methods would apply to either one vehicle or two vehicles of the same type.

1. Drones

This type of maneuvering method includes using a quadcopter drone with a mounted sensor package. There are two potential tests that could be performed using drones. The first test would be using an avoiding drone with a sensor and a second drone that would act as the projectile. The second test would include using an avoiding drone with a sensor and a range of small objects that would act as projectiles. This is displayed in Figures 13 and 14.

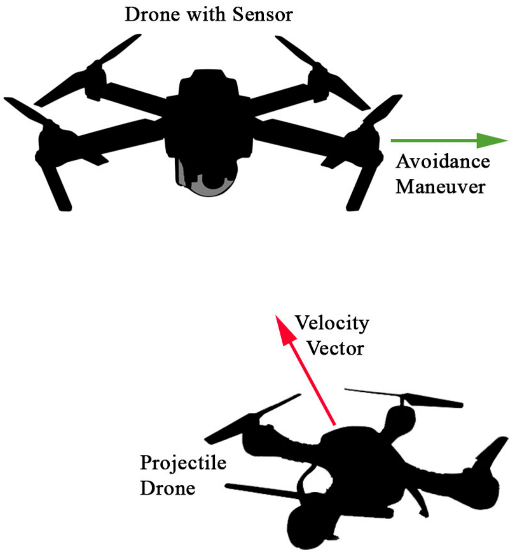

Figure 13

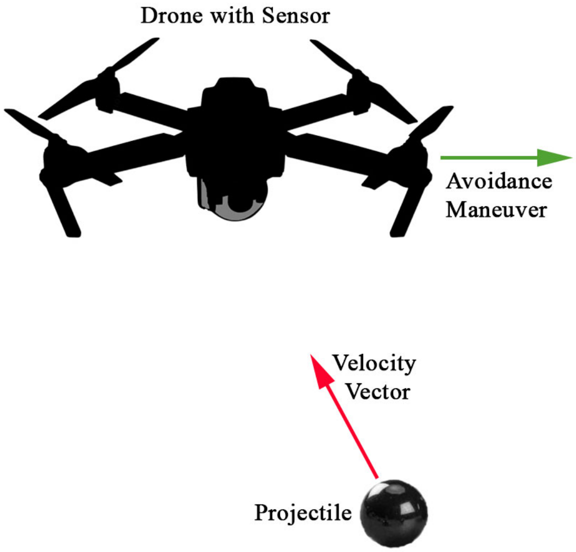

Figure 14

Drones are considered for this test due to their high-speed capabilities which range from 50-200 kilometers per hour, a range of up to 1 kilometer which is large enough for the proposed test environments, and fast reaction times. Three potential drone types that are considered for their high performance capabilities are the Walkera F210 3D, which has a top speed of 80.47 kilometers per hour, the EACHINE Wizard X220, which has a top speed of 109.44 kilometers per hour, and the Walkera Furious 215, which has a top speed of 185.1 kilometers per hour. Furthermore, each one of these drones are equipped with the ability to add a sensor mount.

Using drones as a maneuvering method in an open-air test environment leads to various complexities. A software complexity that will arise will be implementing a simultaneous localization and mapping (SLAM) algorithm. By implementing a SLAM algorithm into the vehicle's software, a map would be constructed of the environment while simultaneously keeping track of the drone's location within it. This would result in the ability to observe a foreign object, calculate its distance, speed and overall trajectory, which would in turn allow the avoiding drone to change its position, bypassing a potential collision.

Pros	**Cons**
Easy construction and command and control	Expensive
High speed capable	Potential difficulty in automating control responses
	High baseline technological competency
	Only usable in open air environment

2. Ballistic Projectile

This type of maneuvering method involves launching or shooting ballistic projectiles at a targeted location to produce the desired collision scenario. Although there are many types of projectiles that could fall under this category for maneuvering, the primary ones that have been considered for this project are cheaply built and easily propelled (small scale pressurized water or air rockets), BB's fired out of a mounted BB gun or pressurized launching device, mechanically propelled small spheres (marbles, tennis balls, etc. shot out of a catapult like device).

The major challenges of producing mechanisms in this category of maneuvering are the limited command and control post launch, added difficulty of constructing launch devices, restricted adaptability of the size of the launch objects, and extreme difficulty of using this method for the main test spacecraft. Because these launched objects are ballistic, they will have set trajectories following the initial launch that will be difficult to manipulate into shapes that represent the collision scenarios desired for the project. It is also unlikely that we will be able to buy any launcher or launching system that can emulate the required specifications, so along the calculations for the desired projectile trajectory, a launching device capable of producing that trajectory would require our construction. Consequently, the size and shape of launched objects will likely be fairly unadaptable following the construction of the optimal launching device. The most principle detriment to using this method of maneuvering is that it is incapable of in flight command and control during flight, so cannot be implemented on the avoidance vehicle without additional maneuvering techniques.

Despite the significant drawbacks of using ballistic projectiles, they also offer an extremely cheap, high speed capable, and easily adaptable solution to this test situation. Even the most expensive of the ballistic options considered are still easy to implement for under a hundred dollars. Similarly, it is also easy to generate high speeds in these launch scenarios, as pressurized air cannons can easily reach velocities larger than 50 $\frac{m}{s}$ even firing large objects like basketballs. The largest advantage of using ballistic projectiles is our capability to combine launching mechanisms with other maneuvering techniques to produce at partial command and control capabilities during the (normally) ballistic trajectories.

Pros	**Cons**
Easiest high speed capabilities	No post launch control
Most options are less expensive	Difficult to generate orbital shapes
Potential to combine with other maneuvering hardware	Potential to not be usable in all environments
Adaptable design options	Only realistic for colliding object
	Safety risk if error/miscalculations in launch

3. Cold Gas Thrust

This maneuvering method involves using a gas expansion thrusting system to move a small test vehicle on one of the low friction environments. Similar to how many spacecraft and launch vehicles currently maneuver on orbit, a cold gas system uses an array of thrusters to control spacecraft movement in all three translational and all three rotational axes. For the purposes of our testing environment control would only be needed for one vertical rotational axis and two translational axes. Cold gas thrusters work based on the principles of conservation of momentum. High pressure gas is stored in a tank and is released from a nozzle in bursts with a specific amount of mass and velocity. This mass and velocity has a momentum that then needs to be accounted for which is done so by an opposite reaction to the spacecraft. In accordance with Newton's third law this momentum interaction can also be described with force interactions. The mass expelled from the nozzle provides a force in the opposite direction that would accelerate the spacecraft. This force is usually specified by the nozzle manufacturer or could be computed using a test stand by mounting the thruster to a force transducer. In any case this force profile for the thruster can then be used in computer models predict and control the motion of the vehicle.

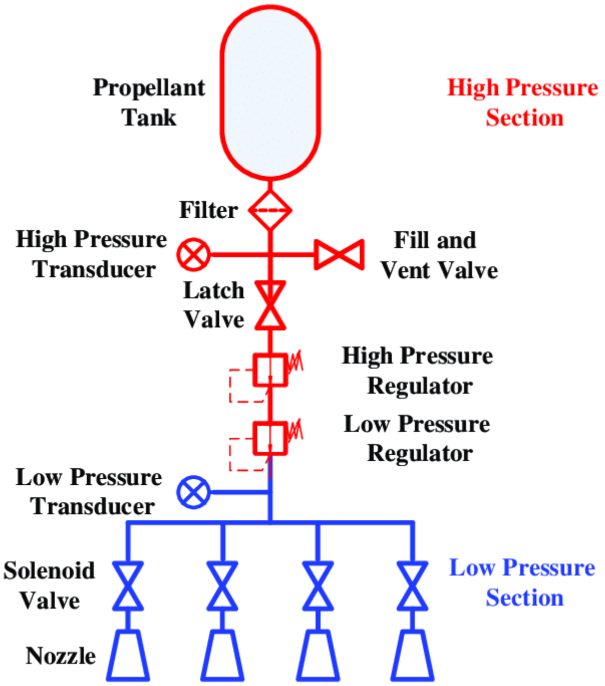

Figure 15 General Cold Gas Propulsion Schematic

One of the biggest benefits of a cold gas thrusting system is its applicability to the real world environment. Using thrusters could increase the overall representativeness of the test as the error in position would be very similar to that of a real spacecraft. The positional error comes from the fact that the force the nozzle exerts may not be exactly what was modelled. One of the biggest challenges in our small test environment with cold gas thrusting would limiting the weight of the maneuvering vehicle. The most ideal way to operate a cold gas system would be to make the vehicle a stand alone system. This would mean that it would carry all of the propellant needed for a test as well as the valves, valves hardware, micro controller, and power. Operating in this way means that the craft needs to carry a large amount of mass with it meaning that parts chosen need to be optimized for the lowest mass possible.

The other primary way of operating this system would be to have the gas and valve hardware stationary on the ground, external to the vehicle. This external propellant source would then be connected to the maneuvering system through flexible hosing meaning that only the thrusters are located on the vehicle. This introduces problems with the stiffness of the tubes providing external forces to the vehicle which would cause problems with the vehicle not responding how it was predicted to. However, the benefit to this system would be that more off the shelf parts could be used. Since the mass of the parts not mounted on the system would not matter cheaper parts could also be used. The decision between internally and externally mounted cold gas propulsion is not as critical as the overall maneuvering system chosen and thus that decision would be made after CDD. Both options will be accounted for in the trade study performed later on this critical element.

Pros	Cons
High speed capable	Difficult to accurately generate a specific force
Cheap	Require replacement after each use
Similar design to a thruster	Potential to damage test items

4. Motors

This method for maneuvering involves using electric motors to drive the vehicle in 2 dimensions. There are two primary ways of doing this depending on the low friction environment used. The first method would apply primarily to the linear rail option. Similar to how 3D printers and laser cutters work, the motors would be mounted on the linear rails and would directly drive the movement of the carriage along the rail. This method is the more simple of the two methods and involves less moving parts. Some of the potential problems with this method involve the interface of the motor to the rail and the weight and inertia of the motors. If the motors do not have a secure interface to the rails they may slip relative to the rail surface.

A different option using electric motors would be to use belts or cables to pull the vehicle on linear rails. These belts or cables would be connected to externally mounted pulleys and then ultimately to the motors externally. This method means that the vehicle does not need to carry the mass of the motors. This allows then for greater accelerations of the test vehicle using similar motors to the previous method. The challenges that it adds are in determining the interaction of the motors and the pulleys, how many motors are needed, and ultimately how best to drive the vehicle. Since he vehicle ultimately needs to be able to translate in two dimensions some clever design would have to be implemented to allow the motors to simultaneously drive the vehicle in each the x and y directions without having the system come to a crashing halt.

Electric motors present their own unique advantages and challenges. For starters they usually provide much higher torque than something like a combustion engine. This is because they are able to provide all their power immediately on demand even from zero initial movement. This is the primary reason for concern with the slipping discussion earlier. Electric motors are also available in a very wide array of options and configurations from many different manufactures. The best option for our group would likely be to use a brush-less DC motor. DC motors in this case would be more desirable as the power provided by the batteries is already DC. If AC induction motors were used the power from the battery would have to be converted into AC power which would involve some extra loss. The decision for a brushed motor versus a brush-less motor is another one of those decision that is not as critical to the success of the project as the overall maneuvering system and would be made later.

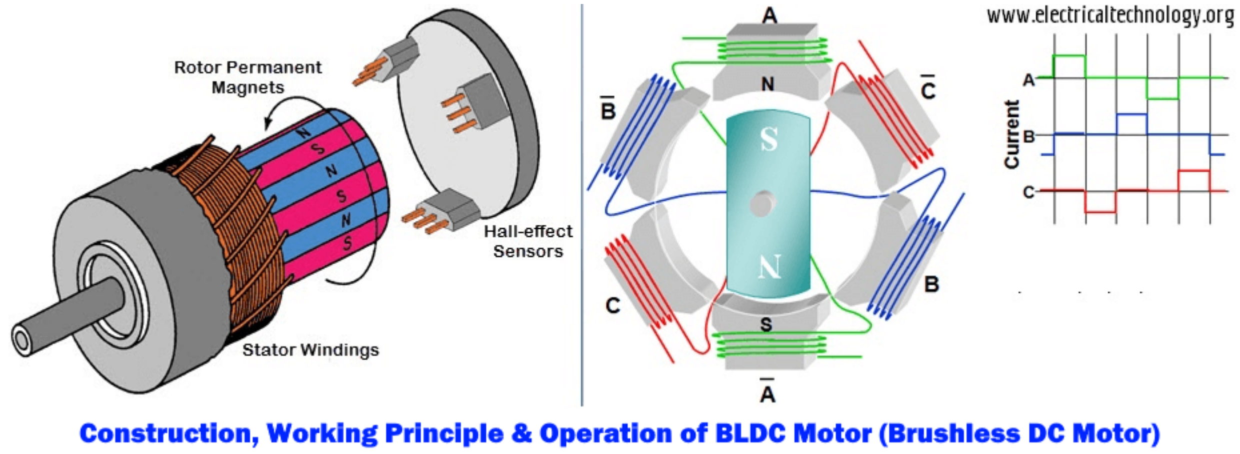

Figure 16 Brushless DC motor Diagram

Pros	Cons
Accurate force generation	Difficult assembly/integration
Electric or gas option	Expensive for high force generation
High speed capable	Heavy motors and magnets
Good heritage in similar test designs	

5. Pneumatic Track

This method for maneuvering involves the creation of a track on a wooden (or other cheap material) base filled with a pneumatic tubing system that offers compressed air thrust to the object guided along the track. The pneumatic tubing system would be hooked to an adjustable air compressor that could provide different pressures, which would correspond to different speeds of the propelled object. Ideally, the track shape would be adjustable for different collision scenarios. Basic top and front views for the fundamental design of this maneuvering method are provided in Figures 17 and 18.

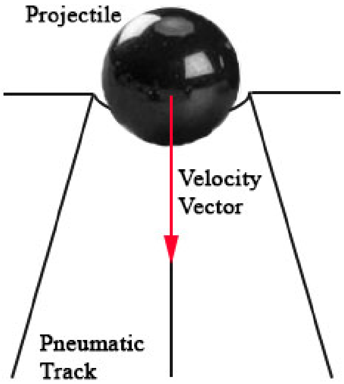

Figure 17 Pneumatic track front view

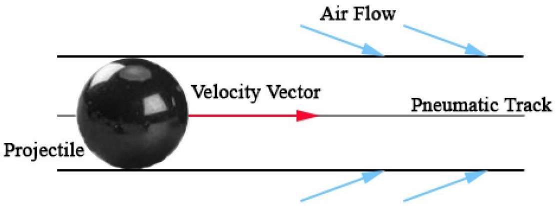

Figure 18 Pneumatic track top view

The main advantages of using a pneumatic track are its high adaptability, accurate force generation, and ability to adjust ballistic projectile trajectories. Because the pneumatic track would be built by CAST, we could design it specifically for most sizes of objects, shapes of trajectories, and speed capabilities. Similarly, it would be fairly easy to calculate the exact pressure that needs to be delivered to ensure a particular object speed. This method also provides the opportunity to create whatever trajectory shapes are most applicable to our system and chosen collision scenarios.

The drawbacks of this choice are its relative expense, potentially difficult assembly, required baseline knowledge, and potential to limit visibility of the object. CAST would need to purchase pneumatic tubing, materials, and a compressor as well as assemble these components into a track that is portable and easy to store. There is not a lot of prior group experience with pneumatic construction, so there is the potential to run into unforeseen obstacles in that arena. The track could also easily obstruct the view of the propelled object in relation to the sensor, or vice versa.

Pros	Cons
Can adjust ballistic projectiles	Relatively expensive
Accurate force generation	Potentially difficult assembly
Highly adjustable design	Required understanding of pneumatic systems
High speed capable	Limited visibility

6. *Software Defined*

A high fidelity physics simulator can be used to propagate the trajectories of both the sensor platform and colliding object. In order to achieve this, the sensor package will first be calibrated and understood with a readily available physical object, such as a basketball. Once the output of the sensor package is understood, representative sensor data can then be simulated and fed to the test bed system. The first advantage of simulation is the capability to run any conjunction scenario. A parametric simulation model would be capable of representing any scenario that happens on orbit. Representative scaling would directly result as no sacrifices would need to be made in approach distance or velocity. The test bed system can then execute its maneuver in any of the previously considered environments. An extension of the test scenario to include ground based databases would then be no issue. A simulation based system could interact with known objects in simulated versions of their real, measured orbits. However, difficulties of simulated conjunctions are plentiful. The simulated system must still be verified with a hardware demonstration. Without empirical demonstration of the validity of the simulation model the system would add no value whatsoever. Therefore, if the software defined method is selected, it must be coupled with another maneuvering method for the collision object, at least initially. This will serve to verify sensor operation and understand the intricacies before incorporating the physics simulation. Sensors must be characterized extremely well in order to properly simulate their response in the orbital environment. Simulating sensor data is a difficult task that would require a deep understanding of the behavior of the chosen sensor, and may be out of the scope of this project. Simulations on this scale represent a significant development effort since several layers of tightly coupled system dynamics must be simulated to properly generate sensor responses.

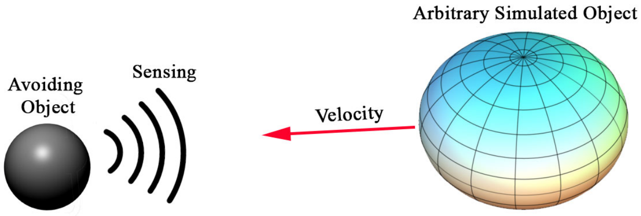

Figure 19 Software defined launching method

Pros	Cons
All orbital scenarios are feasible	Capabilities must still be verified by a hardware test
Reduced impact to budget	Significant development effort
Reduced size constraints	Sensors must be characterized extremely well
Usable in any test environment	
Easily extended to include ground data	

D. Sensor Packages

The ability to sense a potential colliding object is absolutely necessary for CAST to be able to demonstrate that collision avoidance is possible. Choice of sensors to be used in the physical 2D test must include several considerations. The sensor chosen should not exceed the relative capabilities of available sensors that could be used to detect objects on orbit in order to preserve a representative test, requiring research into sensors that would be available to use on board a real spacecraft. However, this does not require the selected sensor to be similar to a sensor that would actually be used on orbit because the different environments have different sensing requirements. It is worthy to note that most sensor packages used on the scale of the 2D physical test environment will likely exceed the capabilities of technologies used on real spacecraft at orbital scales. Despite this, chosen sensor packages can be artificially limited with software in order to preserve a representative and valuable test. The chosen sensor will instead be selected based on its performance in the scope of the chosen 2D testing environment and collision scenario. Each available sensor will act either as an active sensor or a passive sensor. An active sensor will emit a signal (ie. sound, infrared, laser) and detect anything that comes into contact with its reflection. A passive sensor will detect objects without first emitting a source signal. Most of the sensor technologies below act as active sensors but some have passive options as well, such as infrared sensors.

1. Laser Rangefinder

Laser rangefinders (LRF) offer a readily available, highly-developed technology for accurate, long-distance measurements. LRF are typically used for military applications in long-range weaponry or for civilian applications in sports such as golf. Two types of rangefinders were examined to determine their usefulness: laser triangulation sensor and time of flight sensor. Both of these sensors work as an active sensor by emitting a laser. Figure 20 gives a depiction of the triangulation measurement principle, which operates by measuring the change in angle of the incident, reflected beam. While these types of sensors are fairly simple, they are limited in the depth of field and accuracy falls off rapidly with increasing range[14].

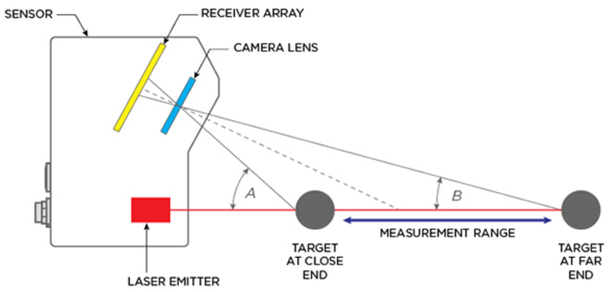

Figure 20 Triangulation Measurement Principle [15]

The time of flight laser rangefinder may be more relevant to our project. These types of sensors operate by measuring the time that the laser takes to travel from the emitter back to the sensor. However, this is often not done directly, but by pulsing the source laser to change the signal over time. Then, the received signal and the signal from the emitter can be compared in order to determine the time of flight. Finally, the speed of light can be used in conjunction with this time of flight to obtain the range. Figure 21 gives a visual depiction of this technology.

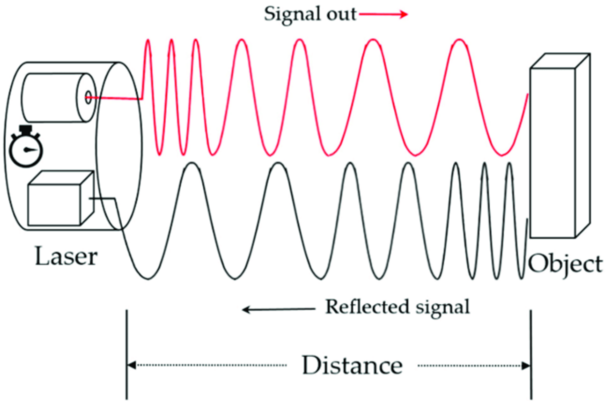

Figure 21 TOF Measurement Principle [16]

From Acuity lasers, "phase measurement is limited in accuracy by the frequency of modulation and the ability to resolve the phase difference between the signals." [14]. This technology is better suited for intermediate range measurements up to 50-100 meters. The FOV of some commercial options is usually under 0.5° which means that precise pointing is required in order to determine range. However, if pointed correctly, this could satisfy DR 1.6.1. For determining velocity of the incoming object, two distance measurements can be differentiated using an on-board clock, making the implementation of a sensor quite simple. Given the often high sample rate of laser rangefinders, this measurement could be repeated in order to get an accurate trajectory prediction, satisfying DR 2.1.

For tackling multiple collision trajectories, the pointing of this rangefinder is not trivial given the reaction time necessary. In order to overcome this, a method of pointing the LRF or combining with a secondary sensor may be necessary.

Pros	Cons
Extremely fast readings	Single beam
High accuracy	Need precise aiming

2. Optical - Visible/IR

Optical sensors can be very simple and cost-effective sensors. They work by utilizing photon interactions to detect and gather information on an object. Optical sensors will work well on the 2D test bed on the ground but will not necessarily work as well in the larger mission in space because they require a light source and depending on where a satellite is in orbit and where the object is there may not be enough light for the object to be detected properly.

An active optical sensor type being considered is a depth sensor which projects infrared dots. A depth sensor's processor then computes the depth of an object by evaluating the density of the dots. Close objects will have a lower density of dots and far objects will have a higher density of dots [17]. A simple image of the projection of these dots can be seen in figure 22 below, ultimately the result from the sensor is a matrix of different distances (the depth) [18]. This is similar to the pin board sculpture toys many people had as a kid, the only difference being that the distance the metal pegs would have to move (the depth) would be calculated using how far apart the infrared dots are.

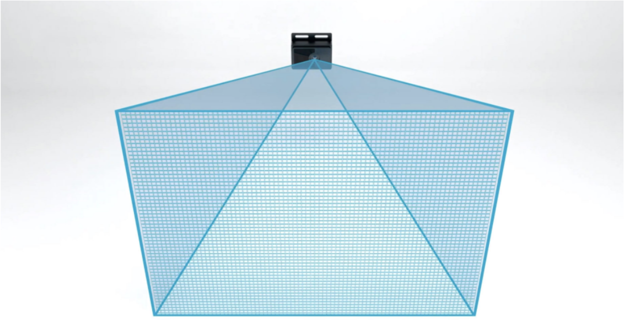

Figure 22 Depth Sensor Infrared Dot Matrix

An image of the infrared dots on a person's hand can be seen in figure 23 below [17]. This image demonstrates the varying density of the infrared dots.

Figure 23 Depth Sensor Infrared Dots on a Hand

Another potential active optical sensor is a motion tracking camera in conjunction with an object tracking software. This would allow the distance that the object is to be calculated and the motion of the object to be tracked. As shown in figure 24 below the sensor will calculate the distance that the object is by measuring the distance that the light travels citejameco.

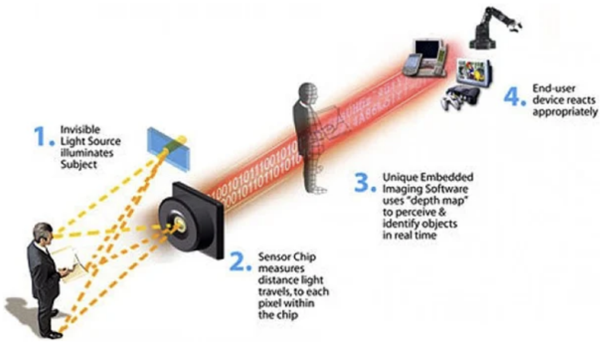

Figure 24 Motion Tracking Camera

In the table below are some pros and cons of using an optical sensor. These pros and cons consider both the larger mission as well as the smaller mission for this academic year.

Pros	Cons
Can collect whole image at once	Requires light source
Wide FOV	Need multiple measurements to get depth/distance measurements
	Affected by weather conditions

3. LiDAR

LiDAR is an active sensor based off of the developments to radar sensing. LiDAR transmits EM pulsed lasers (up to 150,000 times per second) to determine the distance of objects [19]. LiDAR operates essentially as a laser rangefinder that is used to scan an area, rather than provide a 1-D measurement[20]. Two common areas of application for LiDAR are topographic and bathmetric measurements as shown in figure 25[21]. LiDAR has been a proven remote sensor in the space environment. The LiDAR sensor on OSIRUS-REX has a maximum range of 7.5km and can have a detailed resolution of 1cm at that range[22]. Another LiDAR sensor was used by the USAF and US Army that could detect a 1m^2 object about 10,000km away[23]. This technology has a wide array of uses and can be optimized to work for many scenarios.

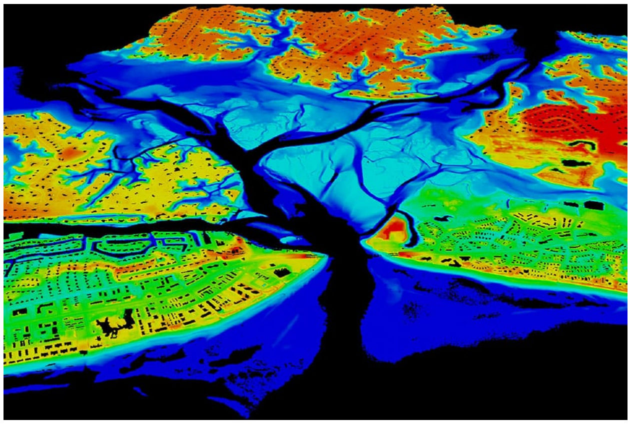

Figure 25 A lidar map of Lynnhaven Inlet, Virginia [24]

Due to the 2D mapping provided by LiDAR systems, this technology would be well suited to meet FR 1. This technology is able to maintain much of the accuracy and distance benefits of the laser rangefinder, while increasing the FOV. However, these benefits come at a cost. In order to provide 2-D data, the source laser must be spread over a greater area. This is usually done by either scanning LiDAR or flash LiDAR. Scanning LiDAR uses mechanical machinery to physically rotate the laser beam and scan the environment. This machinery increases the size of the sensor package.

Additionally, since the laser cannot be simultaneously pointed in two directions at once, this limits the sampling rate for a single measurement position. Flash LiDAR operates by spreading the beam through the use of lenses or other means [25]. By not requiring moving parts, this keeps the size of flash LiDAR packages small. Further, beam width can be sacrificed in order to obtain greater distance measurement – an average sensor will allow for a measurement distance up to 185m away with a beam width of 20° (LeddarTech Vu). Due to the increased complexity over LRF, LiDAR sensors can increase in price to around $700 for commercially available options. Figure 26 gives a quick overview of the differences between the LiDAR technologies.

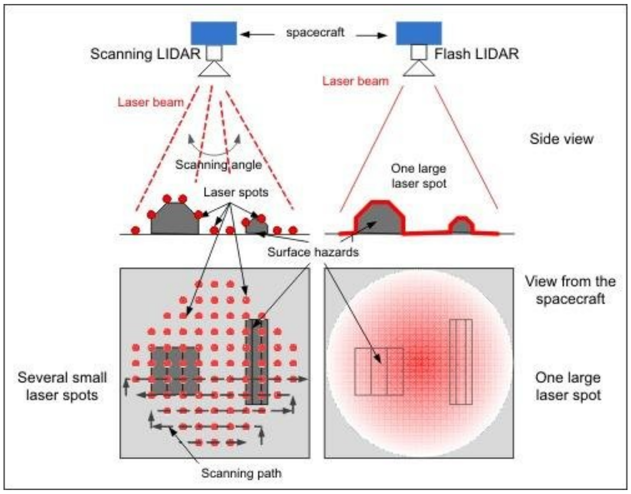

Figure 26 Comparison between scanning and flash LiDAR

This sensor would work well in a space-based orbital environment. However, due to political reasons with transmitting pulses of lasers it may be a poor selection. For an Earth-based test environment, this type of sensor would work well.

Pros	Cons
Can detect smaller objects	Shorter operating distance
High accuracy	Operations are weather dependent
Small package size	Accuracy depends on material properties
No geometry distortions	

4. Radar

Radio detection and ranging also known as Radar is a commonly used sensor in automated systems. Radar is an active sensor via the use of radio waves to provide information about the object's location at a given time. When more than one pulse of radio waves are transmitted, information can be gathered about the objects motion at many different times. Two types of radar systems were chosen as possible designs for this project: the moving target indication pulse radar and the frequency modulated continuous wave radar (or frequency wave modulated continuous wave Doppler radar).

The moving target indication radar (MTI radar) uses a single antenna for transmitting and receiving a signal. The MTI radar is an active radar sensor. The MTI radar utilizes the doppler effect in order to distinguish between stationary and non stationary objects. For an MTI radar, if the frequency of the received signal reflected off the object increases the object is moving towards the radar sensor whereas if the frequency decreases then the object is moving away from the radar.[26] The MTI radar has less cluttered signals because of its ability to distinguish stationary and moving objects, it has no range ambiguity so the location of the object is the objects true location, and an improvement factor is not needed (since no clutter cancellation is needed) [26]. As seen in figure 27 an MTI radar works by transmitting a frequency (in the figure below that is frequency ft) and analyzing the shift in the frequency received in order to determine the change in frequency caused by the moving object [27].

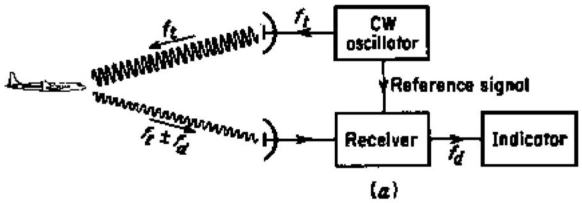

Figure 27 MTI Doppler Shift Explanation

The other kind of radar being considered is the frequency modulated continuous wave radar or frequency modulated continuous wave Doppler radar (FMCW radar) which requires two antennas, one for transmitting and one for receiving. The FMCW radar is an active radar sensor. As opposed to the MTI pulse radar, the FMCW radar is constantly emitting a signal. The frequency of the emitted wave is modulated which gives a unique time for each instant of the wave in order to uncover the time delay between transmission and reception so that the range can be calculated [28]. As seen in figure 28 one way to modulate the wave is by linearly increasing the frequency resulting in a constant rate of change in the transmitted frequency [28].

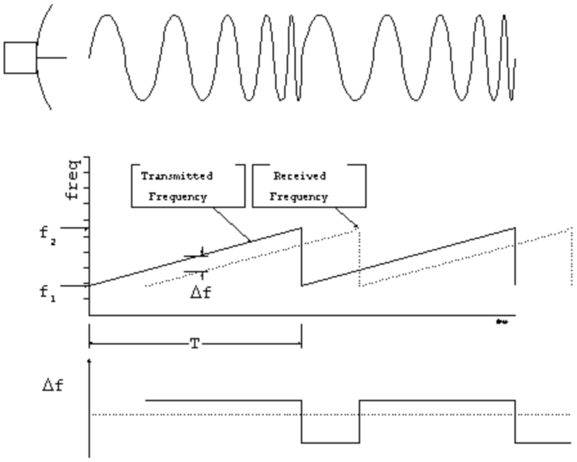

Figure 28 FMCW Linear frequency Increase

Some pros and cons of using radar for both the larger scope mission as well as the smaller scope for the project this year can be seen in the table below.

Pros	Cons
Large range of available frequencies	Decreases usefulness as distance increases
Possible wide beam width	Package size depends on antenna requirements
Weather independent measurements	Object shape changes range of detection

5. Infrared

Infrared sensors can detect infrared radiation that is emitted from bodies that produce heat. Typically a body that is at least 5K will be detected by the infrared sensor[29]. Infrared sensors are the sensors that are typically used in the missile defense field. Other uses of infrared sensors include night-vision goggles, motion detectors, and temperature sensors. An active infrared sensor will utilize an LED light and detect anything that comes into contact with its reflection. A visual of this process may be seen in figure 29. A passive infrared sensor will detect without first emitting an infrared source. For a space detection application, it is important to consider that objects in orbit may not retain much thermal energy and be very close to 0K. This could lead to a very minute different between the IR signature of orbital debris and the background environment. For an Earth-based test environment however, an infrared sensor may be a good option. There are a wide variety of commercial off the shelf high speed of detection infrared sensors available for a relatively low price. This sensor would help meet DR 1.6.1.

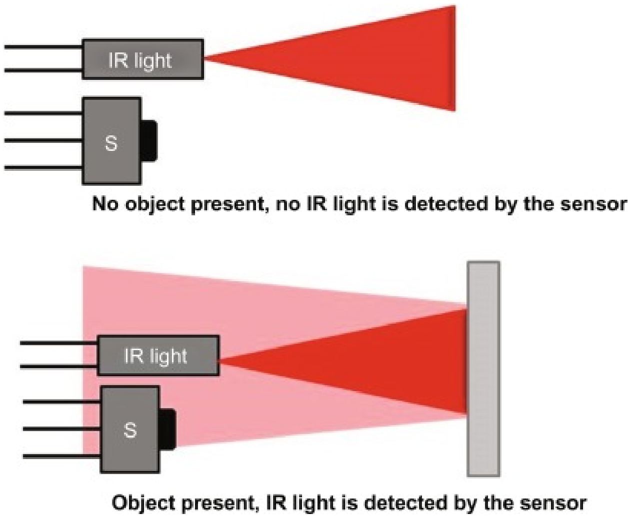

Figure 29 Infrared Active Sensor

Some pros and cons of using an infrared for both the larger scope mission as well as the smaller scope for the project this year can be seen in the table below.

Pros	Cons
Space debris above 5 Kelvin emits IR	Need to have IR emission from secondary object
Inexpensive and readily available	Short Range

6. Ultrasonic

Ultrasonic sensors are active sensors that transmit sound waves. The time between sending the signal and receiving the signal is used to calculate the distance that it traveled. Ultrasonic sensors use this active sensing system by emitting sound waves that are a higher pitch than what a human can hear [30]. For a space based orbital detection system this would be a poor sensor to choose because sound waves do not travel in a vacuum environment. For an Earth-based test environment however, the ultrasonic sensor would work. The high speed ultrasonic sensors have sufficient response times although they are slightly lower than EM wave active sensors such as an active infrared sensor. An advantage over an EM wave emitter however is that ultrasonic may detect a wider range of materials. For instance, ultrasonic sensors can detect clear plastic better than infrared sensors[30]. This type of sensor technology would meet DR 1.6.1.

Pros	Cons
Inexpensive and readily available	Requires medium to travel through
Less susceptible to particle interference	Ideal for low speed and short ranges

V. Trade Study Process and Results

In order to select a baseline design, trade studies must be conducted to understand the effect of each choice on the design. The critical project elements are collision scenario, test environment, maneuvering hardware of the spacecraft object, maneuvering hardware of the collision object, sensor package, and avoidance software. From these options, five were selected to conduct trade studies on: collision scenario, test environment, maneuvering hardware: spacecraft object, maneuvering hardware: collision object, and sensor package. The rationale for selecting each of these is provided at the beginning of each trade study section. Avoidance software was deemed not necessary for a trade study. While this is not trivial parts of the project, it have less of an effect on the selection of the baseline design. Avoidance software can grow to be very complex and the nuances are beyond the scope of this project. While the test-bed will serve as a basis for more complex algorithms in the future, CAST is more concerned with providing a platform for a representative collision scenario to be analyzed. Therefore, simply avoiding the colliding object without considering the optimal method of avoidance is sufficient. Figure 30 gives a flow-down chart for the critical project elements that were selected for a trade study. Note that maneuvering hardware is only listed once, but must be analyzed twice: once for the spacecraft object and once for the collision object.

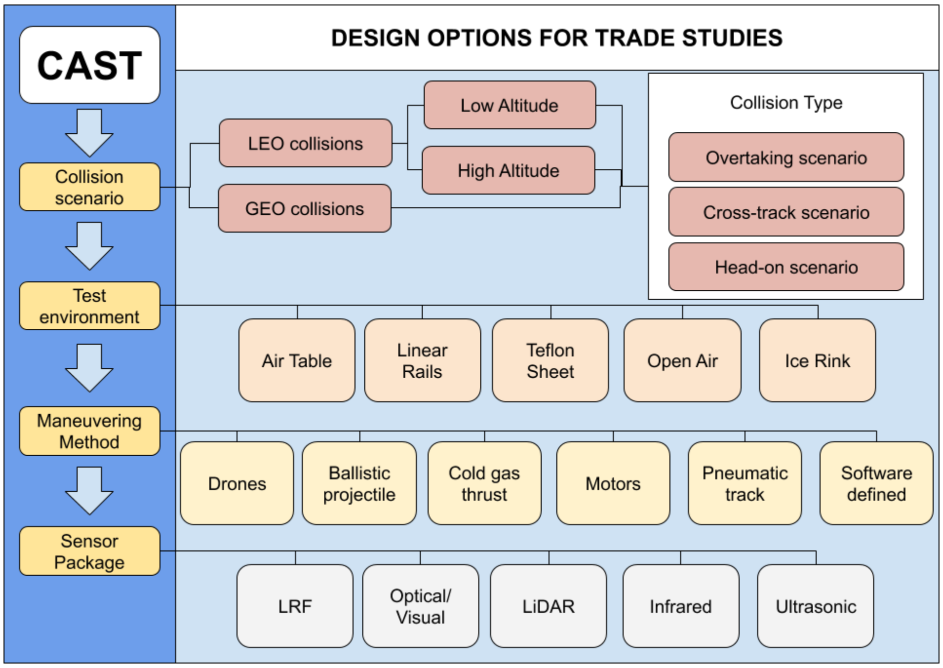

Figure 30 Trade Study Flow-down Chart

A. Collision Scenario

1. Rationale

While analysis of all potential collision scenarios is valuable, CAST must down select in order to maintain a scope that is appropriate for demonstrating the feasibility of the test bed. The scenario chosen is a significant driving factor in many of the parameters of the test environment. If the chosen scenario happens at large relative velocities the test bed must be scaled to prohibitive sizes, while low velocity collisions are extremely rare and wouldn't be representative of the orbital environment. In order to balance the design around both the requirement of a representative scenario and the difficulty of scaling that scenario down to a two dimensional ground test we identified the following criteria.

2. Criteria and Weighting

Four criteria were evaluated during the trade study. The justification for each criteria is explained below along with their relative weight in the trade study. The sum of the weights is one. The criteria, their weights, the driving requirements and a brief description are given in Table 2 below.

2.1 Probability: Probability of collision occurrence is a foundational aspect to consider when deciding which collision scenario to represent in this project. If a collision is extremely rare, then demonstrating that scenario on the ground offers little value to the customer. In scoring the probability criteria we combined a recent sampling of real conjunction risks with a heuristic model on the size of the range of orbits that can cause a conjunction type. The top 100 maximum probability conjunctions gathered from SOCRATES for the week of 09/23/2020 was evaluated, and each scenario was ranked respective to their occurrences in the trade study scoring. A histogram displaying the distribution of relative velocities for this dataset is shown figure 31.

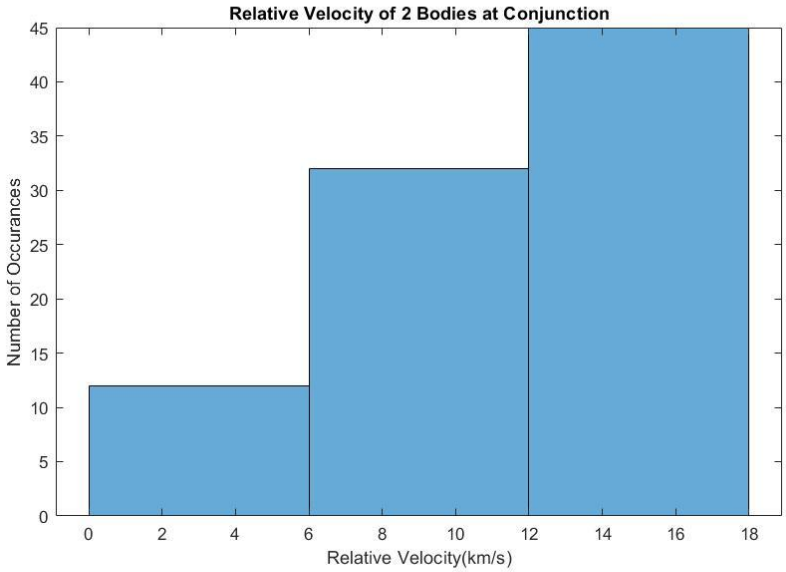

Figure 31 Relative velocity of 100 maximum probablity conjunctions for the week of 09/23/2020

Since the probability of a given scenario occurring is directly tied to how representative the test environment is we give this criteria a weight of 0.4.

2.2 Impact: We weight the impact of a collision by how long the debris cloud will last in orbit. The debris cloud from a collision in LEO will decay in years to decades, while a collision in GEO will leave debris in orbit until it is manually removed. While this is not the only factor that contributes to the impact of a collision it is a sufficient metric given the resource constraints of this study.

Since avoiding a high impact collision provides much more value to both the customer and the space industry in general than avoiding a low impact collision we give this criteria a weight of 0.3.

2.3 Manufacturing Ease: The manufacturability of the testing environment is tied directly to the relative velocities of the collision. A larger relative velocity will require a smaller object moving faster from further away to maintain the similarity characteristics chosen earlier.

While ease of manufacturing is an important consideration in a resource constrained environment, we recognize that its importance is secondary to creating a representative test environment. As such we give this criteria a weight of 0.2.

2.4 Adaptability: The adaptability of a given scenario is measured as how many other scenarios have a relative velocity within 1km/s of the given scenario. This represents how many different scenarios we can demonstrate with a given test set up. Since a single scenario that is extremely representative is more important than a large number of scenarios that are mildly representative we give this criteria a weight of 0.1.

Table 2 Collision Scenario: Weighting

Criteria	Weight	Driving Reqs.	Description
Probability	0.4	DR 1.2	In order to create a the most accurate representative environment, the collision scenario must be highly likely to occur in orbit.
Impact	0.3	DR 1.2	The project provides more valuable insight by avoiding a collision which will create more debris and debris that remains in orbit for longer
Manufacturing Ease	0.2	DR 2.1-2.4	More complex manufacturing will increase the time and cost of the project, but the value added to the project by creating a more representative scenario can outweigh the costs and difficulties of a more complex test bed.
Adaptability	0.1	DR 1.2	Ability to perform tests of other collisions adds value to the final product but other design choices should be considered beforehand.

3. Trade Study

The trade study criteria for the collision scenario is given in Table 3 and the trade study is given in Table 4.

Table 3 Collision Scenario: Scoring

	Scoring				
Criteria	**1**	**2**	**3**	**4**	**5**
Collision Frequency	Rare, low velocity	Somewhat rare, moderate velocity	Frequent, moderate velocity	Frequent, high velocity	Common, very high velocity
Collision Impact	Overtaking decays in years	Overtaking decays in decades or head-on decays in years	Cross track decays in years, or head-on decays in decades, or overtaking will not decay	Cross track decays in decades or head on will not decay	Cross track will not decay
Manufacturing Ease	15 km/s	10 km/s	5 km/s	3 km/s	2 km/s
Adaptability	0%	10%	<20%	<30%	>30%

Table 4 Collision Scenario: Trade Study

	Weight	*LEO*						*GEO*		
		Low Altitude			High Altitude			All Altitudes		
		Over-taking	Cross-track	Head-on	Over-taking	Cross-track	Head-on	Over-taking	Cross-track	Head-on
Collision Frequency	0.4	2	4	5	2	4	5	2	1	2
Collision Impact	0.3	2	2	2	3	3	3	4	4	4
Manufacturing Ease	0.2	4	2	1	4	2	1	5	4	3
Adaptability	0.1	5	3	4	5	4	4	2	5	2
Total	1	2.7	2.9	3.2	3	3.6	3.5	3.2	2.9	2.8

B. Test Environment

1. Rationale

There are several available test environment options to take into account for our design solution, and all of them have significant advantages and disadvantages. The optimal environment is one that enables us to meet all design requirements in the most complete way possible, while also providing characteristics that ease the engineering process when possible. CAST may choose to use a combination of these environments when necessary or possible, but it is important to narrow down the main environment choice for selection and visualization in the baseline design.

2. Criteria and Weighting

Six criteria were evaluated during the trade study. The justification for each criteria is explained below along with their relative weight in the trade study. The criteria, their weights, the driving requirements and a brief description behind the weighting are given Table 5.

2.1 Space Environment Similarity: Some of the most important characteristics of a space collision that are relevant to testing, but difficult to emulate in a test environment are: low friction resistance, high visibility, dynamic lighting, and zero gravity [31]. Each of these that can be represented in the test environment adds value to the test in terms of realism. As such, it is the most important consideration for evaluating test environments.

2.2 Size Limitations: It is important to consider size limitations with respect to each test environment due to the nature of collisions in space having large distances that are potentially difficult to represent even when scaled. Size was assessed by assessing the largest 1 dimensional distance available for each environment. This is an important consideration for the test environments because CAST is attempting to control distances in the test environment.

2.3 Velocity Capabilities: Similarly to size limitations, collisions in space involve velocities that are difficult to represent even when scaled. To evaluate the standard velocity capabilities of each environment, the maximum speeds of vehicles/objects typical in each environment were recorded and scored on a scale relevant to the test bed velocities that are expected during testing. These benchmark values are not necessarily absolute max velocity capabilities in an environment, but rather are assumed to be safe and easily achievable velocities in each environment. This requirement is extremely important because CAST is attempting to control velocities in the test environment.

2.4 Availability: Availability is measured in terms of how many hours per week each test environment would be available. It is important to consider availability because it does not matter if CAST finds the perfect environment if it is never available. However, most environments are at least partially available.

2.5 Maneuvering Option Compatibility: The compatibility of the test environment with other maneuvering options is obviously very important to the overall cohesiveness of the final baseline design. To measure this compatibility, the number of maneuvering options that are feasible to coordinate with each environment is reported.

2.6 Cost of Use: To evaluate cost of use, each environment was broken down into how much it would cost for each meter of material purchased, this was then scaled to a score out of 5 based on the most expensive options. While not heavily weighted, this criterion is important to consider to ensure CAST is meeting budget requirements as much as possible.

Table 5 Test Environment: Weighting

Criteria	Weight	Driving Reqs.	Description
Space Environment Similarity	0.3	DR 1.1-1.2	The more that important characteristics of a real space environment are represented in the test environment, the more the test will be translatable to a real collision scenario, and the easier it will be to duplicate representative maneuvers.
Size Limitations	0.25	DR 1.1-1.2	The environment must be of ample size to represent the scaled distances of a collision in space.
Velocity Capabilities	0.15	DR 1.4	The environment must be capable of representing the scaled speeds of a collision in space.
Availability	0.15	N/A	Testing, construction, clean up, and reiteration is time consuming and necessary for the design process, it is important that we secure a space capable of accommodating for CAST.
Maneuvering Option Compatibility	0.1	N/A	Test environments are not compatible with all the presented maneuvering options. It is only valuable to select the test environment if the accompanied solutions in other design options are compatible.
Cost of Use	0.05	DR 1.8	It is required to stay within the project budget, and some environments contribute to expenses.

3. Trade Study

The trade study for Test Environments is shown in Table 7, and is accompanied by a description of how scoring was calculated in Table 6.

Table 6 Test Environment: Scoring

	Scoring				
Criteria	**1**	**2**	**3**	**4**	**5**
Space Environment Similarity	0	1	2	3	4
Size Limitations	0-1 m	1-3 m	3-6m	6-10m	10+ m
Velocity Capabilities	0-1 m/s	1-3 m/s	3-6 m/s	6-10m/s	10+ m/s
Availability	1 hr	2 hr	3 hr	4 hr	5 hr
Maneuvering Option Compatibility	1	2	3	4	5
Cost of Use	>25 \$/m	25-15 \$/m	15-5 \$/m	5-1 \$/m	Free

Table 7 Test Environment: Trade Study

	Weight	Air Table	Linear Rails	Teflon Sheet	Open Air	Ice Rink
Space Environment Similarity	0.30	4	4	3	2	3
Size Limitations	0.25	1	5	5	5	3
Velocity Capabilities	0.15	5	4.8	3.8	5	5
Availability	0.15	3	5	5	5	1
Maneuvering Option Compatibility	0.10	2	5	4	2	4
Cost of Use	0.05	5	0.2	2.7	5	4.6
Total	1	3.1	4.43	4.005	3.8	3.18

C. Maneuvering Hardware: Spacecraft Object

1. Rationale

The primary object in this test is the maneuvering object that will be avoiding a collision object. This object will require hardware that can produce enough acceleration to avoid an incoming object and cover a vast range in its test environment. The optimal hardware is one that meets the necessary criteria, which are derived from the design requirements. This includes being within the price limit, producing enough force to accelerate the object, having an ideal range of motion, being compatible with the proposed test environment and being able to repeat the test without the need for component alterations, maintenance or replacements.

2. Criteria and Weighting

Six criteria were chosen to evaluate the trade study on the maneuvering hardware: spacecraft object. These criteria and assigned weightings are given below and summarized in table 8.

2.1 Cost: The project funding is limited to $5000 dollars, as stated in DR 1.8. The maneuvering object must have high functioning abilities, but does not require much distance traveled. Since the cost per distance travelled is less important, a weight of 5% is established for cost.

2.2 Complexity: A maneuvering object must be chosen that must satisfy DR 3.1 and 3.2. Since many of the proposed systems are not readily available and may require modifications to satisfy this test, the complexity is given a weight of 10%.

2.3 Force: The maneuvering object must generate enough force to accelerate in the desired direction to avoid the colliding object. Acceleration is a critical component in this design, but is not the dominating factor. Therefore, it is given a weight of 10%.

2.4 Range of Motion: The range of motion of the maneuvering object is the dominating factor of the design, as it must be able to move in a fashion that is representative to the overall scope of this test, as mentioned in DR 1.2 and 3.2. Therefore, a weight of 30% is established.

2.5 Environment Compatibility: As the maneuvering object is the primary object in this test, it is imperative that it is compatible with the proposed test environments. Therefore, it is given a weight of 20%.

2.2 Repeatability: The test system must be fully functional after repeated procedures, as stated in DR 1.7. Having the ability to collect consistent data is crucial to the success and validity of the test. Therefore, repeatability of the maneuvering object is given a weight of 25%.

Table 8 Maneuvering Hardware: Spacecraft Object Weighting

Criteria	Weight	Driving Reqs.	Description
Cost	0.05	DR 1.8	How much the method costs to implement.
Complexity	0.1	DR 3.1, DR 3.2	The greater the complexity of the solution, the worse the score.
Force	0.1	DR 1.1-1.4, DR 3.1	Needs to be able to at least generate enough force to model a smallsat spacecraft thruster
Range of Motion	0.3	DR 1.2, DR 3.2	The number degrees of freedom are available when utilizing this hardware.
Environment Compatibility	0.2	DR 1.5	How many testing environments can the hardware work on?
Repeatability	0.25	DR 1.7	It is important that the maneuver can be repeated consistently.

3. Trade Study

The trade study for the maneuvering hardware: spacecraft object is displayed in table 10. The weights of all the criteria are shown, with scores for each maneuvering method, and their total cost. The maneuvering method with the highest score is likely the one that will be chosen for the final design. A description of how this trade study was scored is displayed in table 9.

Table 9 Maneuvering Hardware: Spacecraft Object Scoring

	Scoring				
Criteria	**1**	**2**	**3**	**4**	**5**
Cost	>$1000	>$500	>$250	>$100	<$100
Complexity	Needs to be developed from scratch/no known working examples	Requires significant design considerations and machining, but has been accomplished before	Multiple working examples to base design off of. Some machining required	Requires minor assembly from readily available solutions	Commercially available
Force	<25N	25-50N	50-100N	100-200N	>200N
Range of Motion	Device can only move in one direction	Device can move in two directions	Device can move in three directions	Device can move in all directions in 2D plane	Device can move in all directions in 3D plane
Environment Compatibility	1 environment	2 environments	3 environments	4 environments	5 environments
Repeatability	Can only perform the test once without extensive component maintenance, alterations or replacements	Can perform the test once with significant required maintenance after each set	Can perform the test with minimal required maintenance after each set	Can perform the test more than once, with minimal amounts of maintenance/ alterations required	Can perform the test multiple times without the need for part adjustments or replacements

Table 10 Maneuvering Hardware: Spacecraft Object Trade Study

	Weight	Drones	Cold Gas Thruster	Motors	Pneumatic Track
Cost	0.05	2	3	3	3
Complexity	0.1	5	2	4	2
Acceleration	0.1	1	1	2	5
Range of Motion	0.3	5	3	4	1
Environment Compatibility	0.2	1	4	1	1
Repeatability	0.25	2	3	5	4
Total	1	2.9	2.9	3.4	2.35

D. Maneuvering Hardware: Collision Object

1. Rationale

The collision object, which will be launched at our spacecraft object, requires hardware to accelerate it to the necessary minimum velocity before collision. The optimal launching method is one that allows for a high/constant velocity, is repeatable and adjustable, and works in a variety of testing environments. The options for this trade study are pulled from the maneuvering hardware design options, as the various options are applicable to both the avoiding and colliding object. However, the criteria and weighting for this study varies due to the greater distance traveled, the size of colliding object, and the consistency at which a measurable velocity can be attained. Additionally, in order to keep the scope of this project feasible, the maneuvering hardware needs to be relatively simple to implement and remain within budget.

2. Criteria and Weighting

Six criteria were chosen to evaluate the trade study on the maneuvering hardware: spacecraft object. These criteria and assigned weightings are given below and summarized in table 11.

2.1 Speed: The velocity of the colliding object is critical for the success of this project. The maneuvering hardware for the collision object must be able of accurately producing a minimum velocity as specified in the collision scenario. Since this is dominating factor in the choice of maneuvering method for the colliding object, it is given a weight of 20%.

2.2 Complexity: The maneuvering method for the colliding object must be able to create a collision consistently as stated in DR 1.5. The complexity of the maneuvering method chosen will have significant impact on the robustness of the design and ease of implementation. Since there are few methods readily available to launch an object of arbitrary size at the avoiding object, there is risk in the engineering that is needed to support these options. In order to mitigate this risk, complexity is given a weight of 25%.

2.3 Environment Compatibility: Some maneuvering method for the colliding objects are not compatible with some testing environments. In order to account for this, the versatility of each launching method must be analyzed. The number of environments each maneuvering method is compatible with will be given in this criteria. In order to obtain a collision to satisfy DR 1.5, the maneuvering method for the colliding object must be compatible with the test environment, and therefore compatibility is given a weighting of 15%.

2.4 Repeatability: The repeatability of the maneuvering method for the colliding object is critical in order to satisfy DR 1.4 and 1.7. It will be difficult to obtain valid data if the test cannot be repeated consistently within the bounds set by these requirements. Since this data is critical to characterizing the validity of the testbed, the repeatability is given a weighting of 20%.

2.5 Cost: The total budget for this project is $5000 and the maneuvering method for the colliding object has the potential to cost a significant portion of the project. The distance the colliding object has to be maneuvered is much greater than the range of the avoiding object, so there is the potential for greater expense. That is why cost is given a weight of 10%.

2.6 Safety: When accelerating an object to high velocities, there is a potential safety concern. This safety concern applies to both people involved in testing and the risk of damaging the avoiding object. Therefore, safety was given a weighting of 10%.

Table 11 Maneuvering Hardware: Collision Object Weighting

Criteria	Weight	Driving Reqs.	Description
Speed	0.2	DR 1.1, 1.2, 1.3, 1.4	The collision object needs to be able to reach a velocity representative of the scaled down collision scenario.
Complexity	0.25	DR 1.5	With the potential to travel great distances, the launching method needs to be robust.
Environment Compatibility	0.15	DR 1.5	The number of test environments that the maneuvering hardware can operate on
Repeatability	0.2	DR 1.4, 1.7	The collision needs to occur consistently.
Cost	0.1	N/A	In order to stay under budget we need to be conscious of budget.
Safety	0.1	N/A	How risky is the launching method to both hardware and people?

Table 12 Maneuvering Hardware: Collision Object Scoring

	Scoring				
Criteria	**1**	**2**	**3**	**4**	**5**
Speed	0-5 m/s	5 - 15 m/s	15 - 30 m/s	30 - 40 m/s	>40 m/s
Complexity	Needs to be developed from scratch/no known working examples	Requires significant design considerations and machining, but has been accomplished before	Multiple working examples to base design off of. Some machining required	Requires minor assembly from readily available solutions	Commercially available
Environment Compatibility	1	2	3	4	5
Repeatability	Can perform test once before needing to replace major components or fabricate new ones	Requires significant time to reset test environment to original state. Likely to put testing schedule on hold between runs	Can repeat tests with some time between each test devoted to resetting the test environment	Can repeat tests multiple times in a row. Small portion of time required between sets of tests	Can repeat tests with no alterations to the testbed between runs
Cost	>$1000	>$500	>$250	>$100	<$100
Safety	Potentially unsafe/large risk of damaging equipment	Requires large amounts of risk management in planning to ensure a safe test	Requires special equipment and precautions	Requires minimal safety equipment/precautions	Poses no safety risk

3. Trade Study

The trade study for the maneuvering hardware for the colliding object is given in table 13, the scoring description for this trade study can be found in table 12.

Table 13 Maneuvering Hardware: Collision Object Trade Study

	Weight	Drones	Ballistic Projectile	Cold Gas Thrust	Motors	Pneumatic Track	Software-Defined
Speed	0.2	4	5	3	3	5	5
Complexity	0.25	5	4	3	2	3	2
Environment Compatibility	0.15	1	5	3	2	5	5
Repeatability	0.2	2	4	4	5	4	5
Cost	0.1	2	3	3	4	2	5
Safety	0.1	1	3	3	4	3	5
Total	1	2.9	4.15	3.2	3.2	3.6	4.25

E. Sensors

1. Rationale

The sensor technology used will be important for providing constraints on software. This trade study will investigate the capabilities and specifications of different available sensor technologies that come in commercial off the shelf packages. The optimal sensor has a long range, high sample rate, large field of view (FOV), and low cost.

2. Criteria and Weighting

Four criteria were chosen to evaluate the trade study on the sensor technology. These criteria and assigned weightings are given below and summarized in table 14.

2.1 Range: The maximum range of the sensor technology is an important factor to investigate. Due to the potential options of the testbed and testing environment, it is important to ensure that the selected sensor technology has the capability to sense the entire distance of the testbed. Due to the importance the range requirement for the sensor technology it was weighted at 45%.

2.2 Cost: The sensor technology must not run too expensive to cause the project to go over-budget. Considering the price of the sensor technology will be important to ensure a cost-feasible sensor technology is selected. Due to the available budget of $5,000, the cost was weighted at 10%.

2.3 Sample Rate: The sample rate of the sensor technology is important when trying to sense objects moving at high speeds. If the sensor takes samples of speed and distance at too slow of an interval, then the collision avoidance software will not have the data in time to make a decision to move or not. Due to the importance of collecting data in time the sample rate was weighted at 30%.

2.4 Field of View (FOV): The field of view is an important consideration to ensure that the sensor can detect a range of space where objects may come from. The larger the field of view, the more objects the sensor technology will be able to detect. Due to the benefit of an increased field of view it was weighted at 15%.

Table 14 Sensors: Weighting

Criteria	Weight	Driving Reqs.	Description
Range	0.45	DR 1.3, DR 1.7	The sensors need to be able to detect the object at a far enough distance so that a successful maneuver can be made. This range must also scale from the space environment to the 2D testbed environment.
Cost	0.1	DR 1.8	It is required that the project remains within the project budget, the sensors contribute to the cost.
Sample Rate	0.3	DR 1.3, DR 2.1	The sample rate dictates whether or not there will me enough measurements in a sufficient amount of time.
FOV	0.15	DR 1.2	The FOV determines the angle that is observable by the sensor. The object must be within this angle for the sensor to pick it up.

Table 15 Sensors: Scoring

	Scoring				
Criteria	**1**	**2**	**3**	**4**	**5**
Range	<25 m	>25 m	>50 m	>100 m	>150 m
Cost	>$2000	>$1000	>$500	>$100	<$100
Sample Rate	<10 Hz	<100 Hz	<500 Hz	<1 kHz	>1 kHz
FOV	0-5 deg	5 - 15 deg	15 - 25 deg	25 - 35 deg	>35 deg

3. Trade Study

The trade study for the sensor technology is given in table 16, the scoring description for this trade study can be found in table 15.

Table 16 Maneuvering Hardware: Collision Object Trade Study

	Weight	Laser Rangefinder	Optical/Visual IR	LiDAR	Radar	Infrared	Ultrasonic
Range	0.45	4	1	5	4	1	1
Cost	0.1	4	3	3	4	4	4
Sample Rate	0.3	4	3	2	2	3	1
FOV	0.15	1	5	3	3	1	2
Total	1	3.55	2.4	3.6	3.25	1.9	1.75

VI. Selection of Baseline Design

In order to select a baseline design, the results from each study must be evaluated and synthesized into a coherent design. Once the baseline design is established, variations on this design are presented to gain an understanding of the alternative design. This also serves to make sure the trade studies were evaluated fairly, which is important given the wide range of possible designs.

A. Evaluation of Trade Studies

With all trade studies completed, the results from each are discussed below:

1. Collision Scenario

When interpreting the results of the collision scenario trade study it is important to note that these parameters are continuous over the range of LEO altitudes, with GEO representing a significant outlier in that GEO conjunction frequencies are on the same scale as LEO frequencies. With this in mind the highest scoring categories are cross track LEO High Altitude, and head on LEO High Altitude, taking the top two spots with scores of 3.6/5, and 3.5/5 respectively. One additional piece of information deemed important, but not able to be included in this study, is the the 2009 collision between Iridium-33 and Kosmos-2251 at 800 km with a cross track conjunction angle. While the example of a collision would be valuable to analyze, it falls outside the ranges recommended by the trade study. As such the formal recommendation is to build the test bed to scale a LEO High Altitude Cross-track conjunction, with a large conjunction angle in the cross-track designation. An appropriate altitude for a collision scenario in this range would be 1200 km. This project element will affect the satisfaction of FR1.

2. Test Environment

The highest scoring environment is the linear rail environment with a score of 4.43/5. This environment is capable of imitating the space environment characteristics of low friction, lighting, and zero-gravity. The high visibility characteristic of the space environment has the potential to be limited given the physical set-up of the test environment. For example, the rails have the potential to block the line of sight of the sensor. However, if the sensor package is carefully oriented on the linear rails so that the line of sight is free of the rails, then this risk is mitigated. There are various lengths of linear rails commercially available and these are capable of velocities up to 9 m/s. After it has been assembled it is available all the time. Finally, it is compatible with all maneuvering options except drones. The biggest downside is that it is the most expensive environment per meter of provided length, but it is still well within the budget for what we are willing to spend on the environment. This cost risk is mitigated by the much lesser range of motion required by the spacecraft object relative to that of the collision object. This project element will affect satisfaction of FR1.

3. Maneuvering Hardware: Spacecraft Object

The highest scoring maneuvering hardware for the spacecraft object are the motors with a score of 3.4/5. This is due to repeatability, range of motion, and low complexity offered. When used in a configuration similar to a 3D printer or 2D linear gantry, motors will allow complete control authority over the maneuvering object. However, they are limited in compatibility with the testing environment. They can only be utilized in the linear rail, with two possible configurations. Either the sensor package is mounted on some rover type base that uses motors to traverse across a surface, or they use belts/chains to drive the object package on set movement paths. Cold gas thrusters were the next best option, and offer movement solutions for the ice rink, Teflon sheet, or air table environments. This project element will affect satisfaction of FR3.

4. Maneuvering Hardware: Collision Object

The highest scoring option was the software defined launch with a score of 4.25/5, with the ballistic projectile as a close runner-up at 4.15/5. This is due largely to the flexibility of a software defined collision to handle whatever scenario is desired. While the complexity of the software defined collision is poor, and will require significant software development, it can be implemented on any of the desired testing environments. Additionally, it provides a significant addition of value to the project, as a greater range of collision scenarios can be tested and the results can more easily be related back to the 2D and 3D simulations. Finally, a software-defined collision will allow more flexibility in the future of this project, as different sensor technology can be assessed by varying the uncertainty, detection distance, and other critical sensor parameters. This project element will affect satisfaction of FR1 and FR2.

5. Sensor Package

The highest scoring sensor technology was LiDAR with a score of 3.6/5. Laser Rangefinder and Radar were close in the scoring with an overall score of 3.55/5 and 3.25/5 respectively. These sensor technologies operate based off of similar principles so the similar scoring makes sense. LiDAR is capable of sensing objects at long ranges that makes it valuable for the testbed environment. LiDAR was lacking the most in the sample rate. The FOV and cost for LiDAR make it a promising sensing technology. Figure 32 shows the difference between a high-resolution LiDAR sensor compared to a high-resolution Radar sensor. This difference will be key in object detection and also highlights the advantage that LiDAR has over Radar[32].

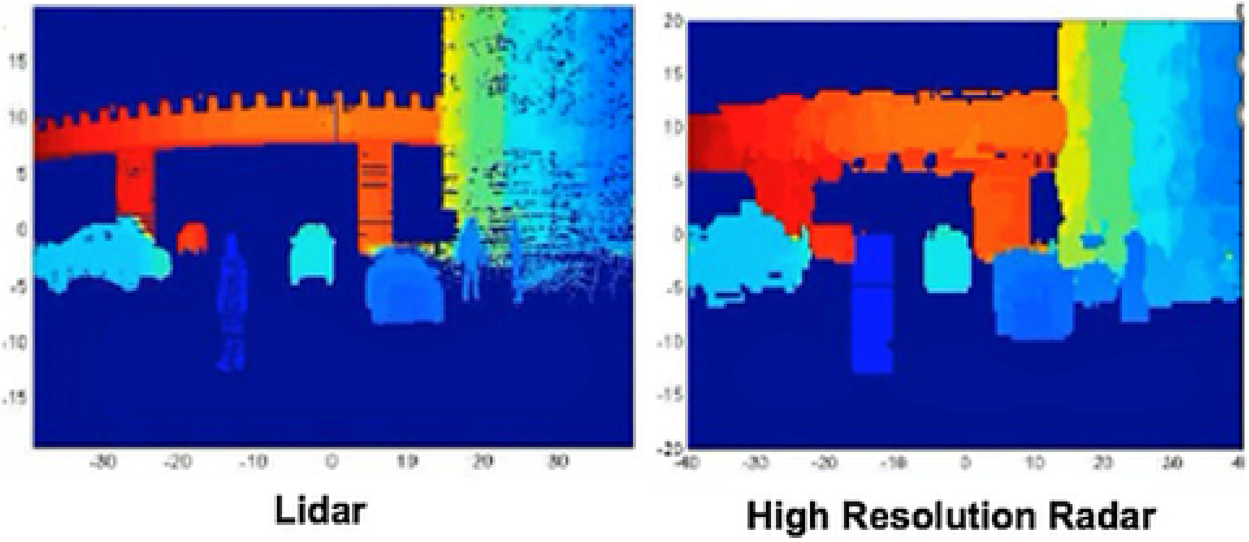

Figure 32 LiDAR/Radar Comparison

B. Synthesis of Baseline Design

Putting all the components together, the baseline design would be comprised of a 2-axis linear motion machine that supports the sensor package. This would allow the sensor to be moved in any direction in a 2D plane consistently.

The sensor package selected for this design will utilize LiDAR technology. Initially, a physical object of arbitrary but measurable size would be used to verify sensor operation and data output. For example, a basketball could be used to classify and understand the sensor output. This will serve as the first line of validation. A detect and react algorithm will then be developed in order to avoid a low velocity object approaching the sensing package on the the path of the line of sight of the sensor.

After this detect and react algorithm is implemented, the data fed from the sensor into the algorithm can be modified in order to emulate an 1200 km altitude cross-track collision occurring around 7 km/s. This relative velocity will be scaled given the maximum range of the sensor package, which has the ability to create a testing environment with a range greater than 100m. This prevents using data that exceeds the capability of the sensor package in the collision avoidance algorithm. Finally, the movement of the spacecraft object can be compared to the collision information to visually verify if the collision occurred. Overall, this will allow the maneuvering hardware to assess the reaction maneuvers that a spacecraft could take to avoid an incoming collision, rather than verify the sensor selection, which is beyond the scope of this project.

C. Possible variations

With the limited test environments available for the motor spacecraft maneuvering option, a reasonable alternative will also be presented. The next highest scoring maneuvering option for the spacecraft object was a tie between drones and the cold-gas thruster. Due to the complications of air-resistance when doing an aerial test, the cold gas thruster method is favored. These could be implemented on linear rails to provide a low friction environment, or paired with the next highest scoring test environment, the Teflon sheet. Although the cold gas thrusters would likely need to be refilled frequently, three thrusters oriented 120° apart would allow for complete control authority on a 2-D, low-friction plane. These options will only be examined if the current idea of a software defined collision is deemed unacceptable by the customer.

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