Team 81 Failure Investigation Report from the 2022 IREC

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1 Introduction

Worcester Polytechnic Institute's High Power Rocketry Club (WPI HPRC) is WPI's largest engineering club and only competition rocketry organization. The club was founded in 2018 to compete in NASA University Student Launch Initiative. Having grown to well over 100 members in the years since, in 2021 HPRC was accepted to compete in the 2022 Spaceport America Cup.

Figure 1 The team with the vehicle prior to launch

The Aquila project, consisting of rocket Altair, and its payload Tarazed, were developed to compete in the 10k Commercial off-the-shelf category, tasked with flying to 10,000 ft using commercially available rocket motors. The vehicle was launched on the second day of launches at the Cup and experienced a failure causing it to break apart during flight.

This document details the investigation into this failure, the conclusion as to the cause, as well as a series of recommendations to mitigate the occurrence of similar failures in the future. Section 2 presents an overview of the vehicle itself. Section 3 describes in detail the failure itself using photos and recovered data to establish a timeline. Section 4 outlines the process of the root cause analysis and all failure modes considered. Finally, Section 5 establishes contributing factors and provides recommendations for the future.

2 Vehicle Overview

Altair stood at 134 inches tall, with a 6.17 inch diameter airframe, and weighed 68.1 lb at liftoff. The vehicle used a CTI M1800 solid rocket motor for propulsion.

Figure 2 Vehicle Livery

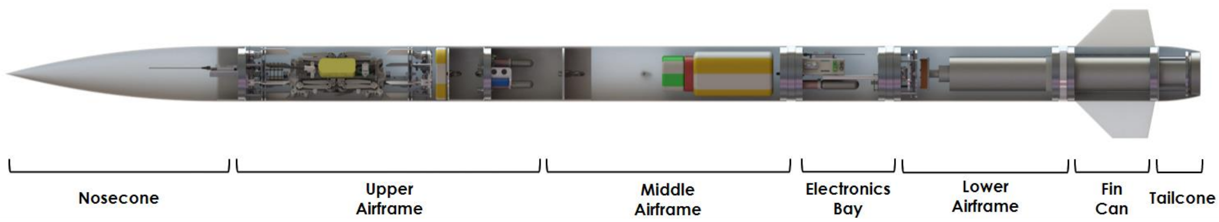

Figure 3 Vehicle Cross Section

The vehicle was split into multiple sections; the nosecone and upper airframe contained the payload. The middle airframe contained the drogue and main parachutes, and recovery hardware. The electronics bay contained the recovery electronics, GPS tracker, and telemetry antenna. The lower airframe contained the airbrake system, avionics stack, and vibration datalogger, and the tailcone held the motor retention system. The vehicle made use of several innovative systems, including a single end deployment recovery system, actively controlled airbrakes, and a novel new airframe attachment method.

The payload, Tarazed, consisted of a recovery bay, a piston, and a retention system. The ends of the payload retention system contained the stabilization system, with the inside containing the quadcopter, a gripper mechanism, an arm deployment mechanism, a parachute release mechanism, plus batteries and electronics. The payload was designed to descend separately from the rocket, land, then orient and deploy the quadcopter. From here, the quadcopter was to locate the rocket via a radio beacon and transmit its location back to the team on the ground.

3 Failure Description

The vehicle successfully lifted off from pad 6 on bank A at 12:24pm MDT on Friday June 24th, 2022. At T+ 4.73 seconds, the exhaust from the motor began to visibly tail off, and the exhaust plume had nearly disappeared when, at T+ 5.37 seconds and an estimated altitude of 1960 ft, first movement of the nosecone is visible.

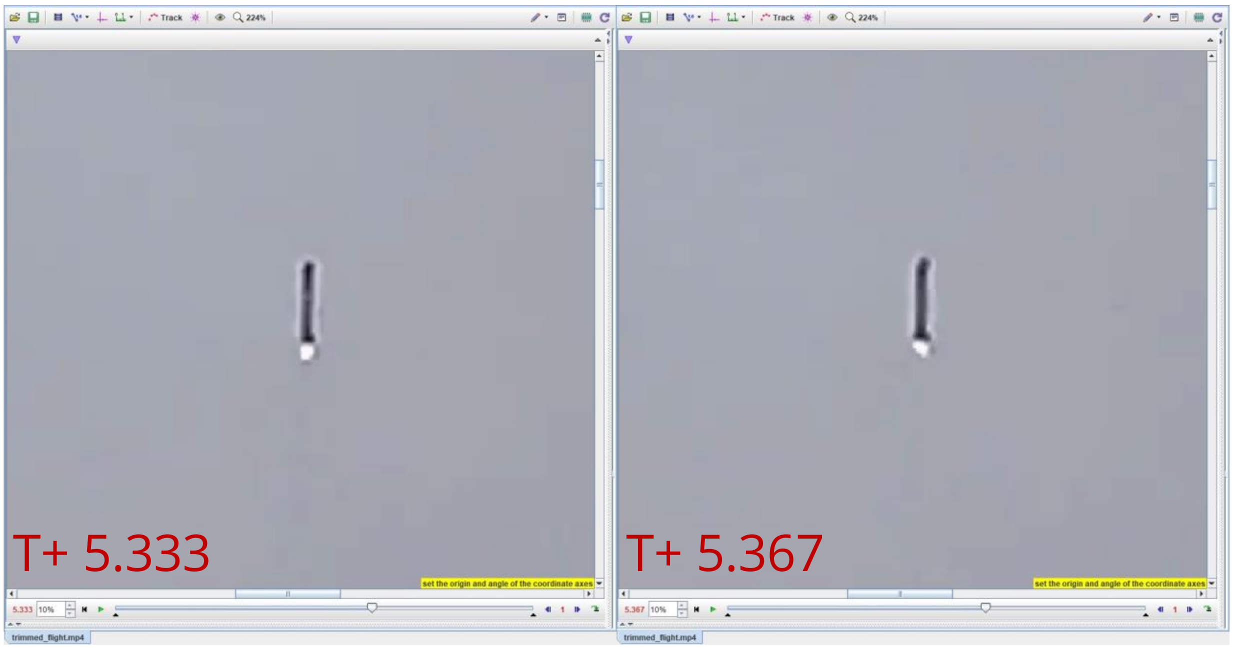

Figure 4 First Movement of Nosecone

The nosecone proceeds to eject from the vehicle, followed by the payload. The nosecone is separated from the payload before the payload fully exits the bay at T+ 5.47 seconds.

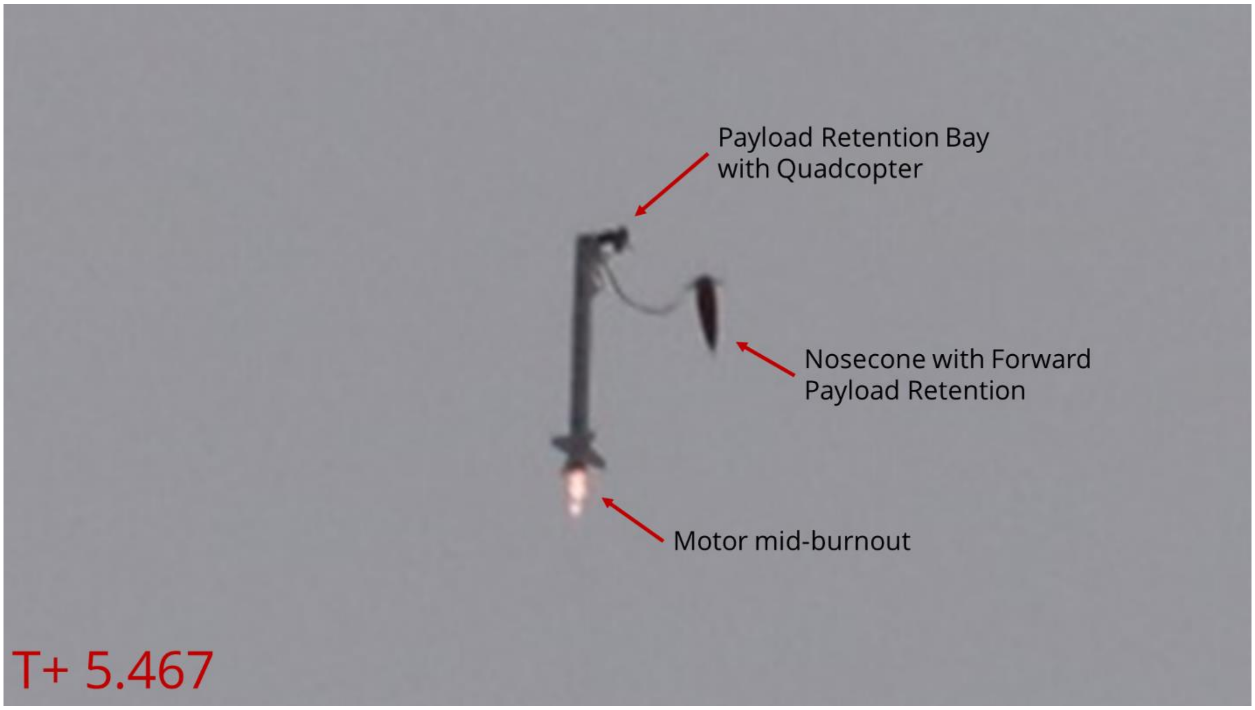

Figure 5 T+ 5.467

The payload retention system, parachute, and piston all continue to eject from the airframe. Due to aerodynamic forces caused by the payload exiting the airframe, the lower airframe coupling fails at T+ 5.50 seconds, causing the electronics bay, middle, and upper airframes to fall away from the lower airframe and fin can. The payload quadcopter also separates from the retention system.

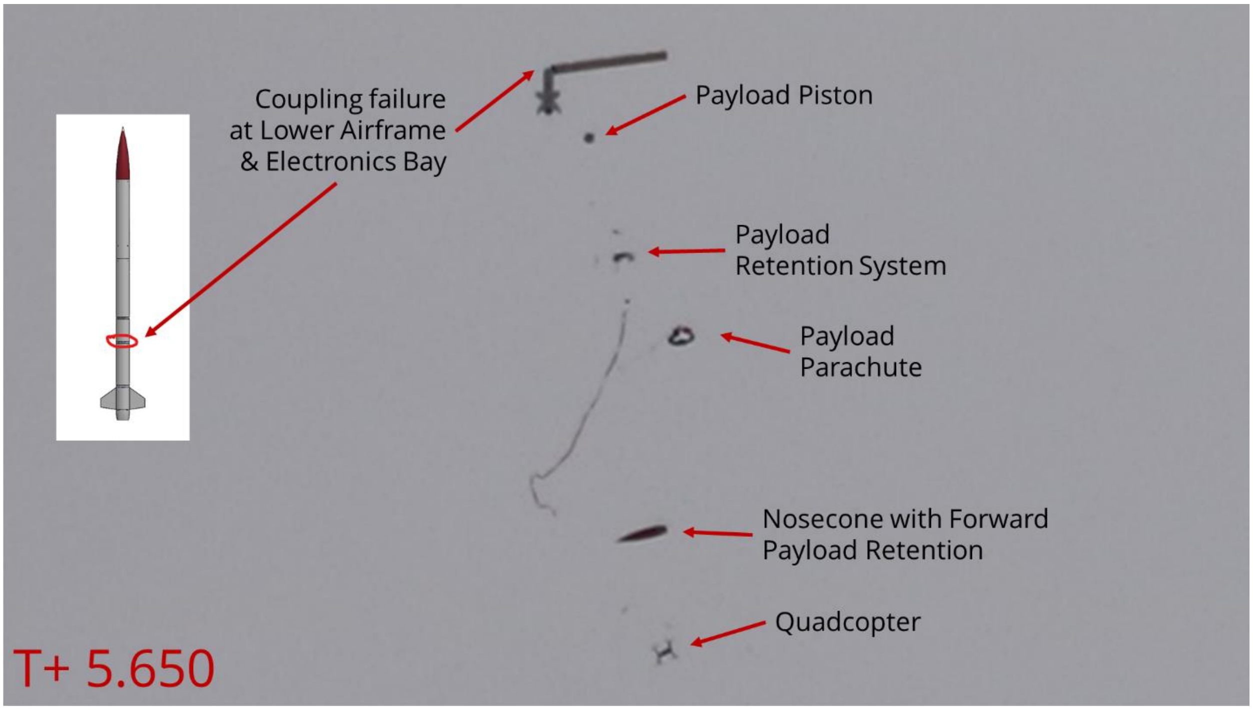

Figure 6 T+ 5.650

The upper and middle airframes separate at T+ 5.72 seconds, releasing the rocket recovery system consisting of the drogue and main parachutes, as well as all shock cord. All parachutes rip free of their shock cord or mounting points to the payload or airframe sections and fall freely. The lower airframe and fin can remain aerodynamically stable and continue to ascend.

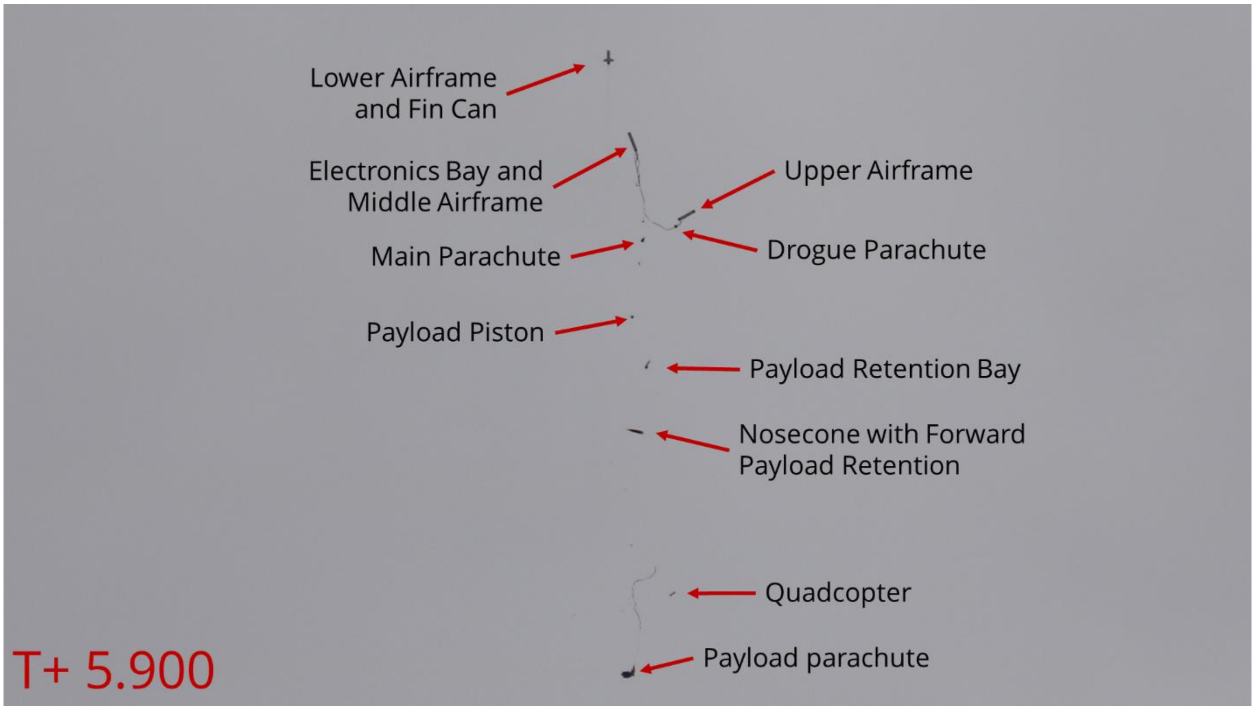

Figure 7 T+ 5.900

Telemetry received by the ground station confirms these series of events. Plotting the magnitude of the total acceleration, we see burnout take place at T+ 4.97 seconds, and the minimum acceleration where the vehicle is just experiencing drag at T+ 5.33 seconds, just before nosecone separation per the pictures. Then the acceleration spikes back up as the drag increases due to breakup, before data is lost. It should be noted that despite the exact matchup between the T+ 5.333 second event in Figure 4 and Figure 8, the liftoff times were reached independently. The acceleration data was not used to reconstruct liftoff time for the photos/videos or vice versa. However, that the data matches up so well is encouraging.

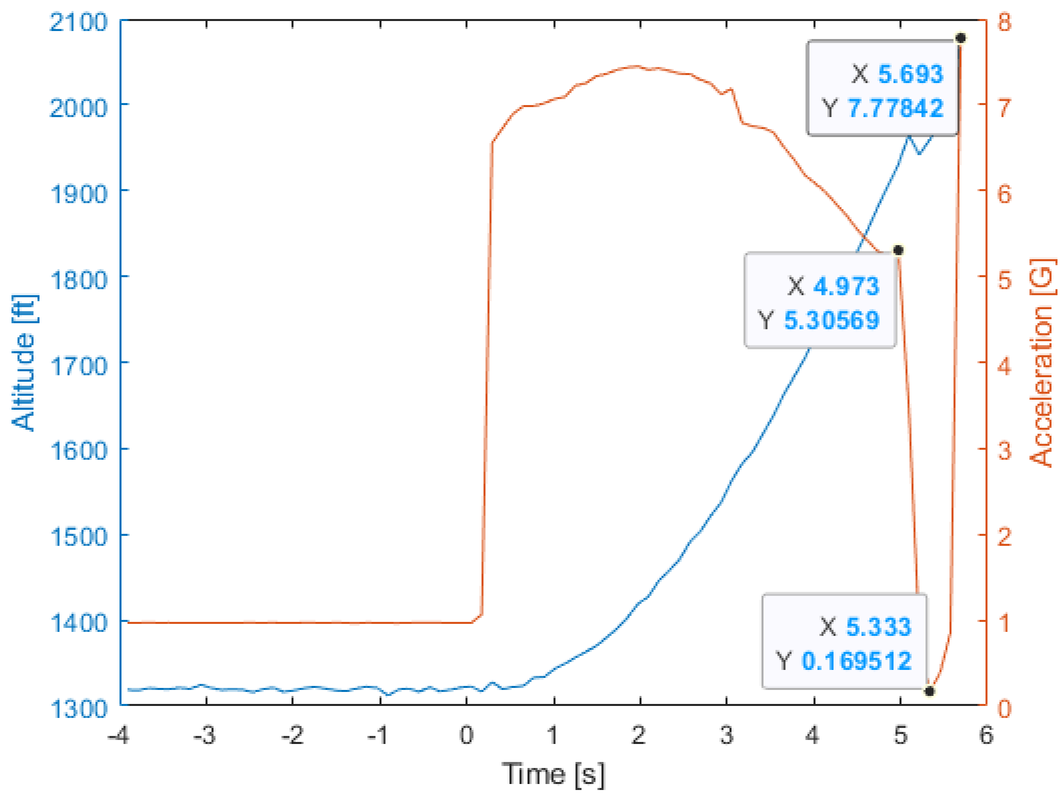

Figure 8 Altitude and Total Acceleration Data from Flight

The major events of the failure occurred over 0.35 seconds, from T+ 5.37 to T+ 5.72. The airframe sections and payload components then fell ballistically due to the parachutes breaking free from all major sections. The electronics bay and middle airframe, upper airframe, nosecone, and quadcopter were recovered without significant additional damage due to ground impact.

Figure 9 Middle Airframe and Electronics Bay

Figure 10 Nosecone

Figure 11 Quadcopter

The payload retention system sustained more significant damage, landing in a small divot and bending the bulkhead and spine.

Figure 12 Payload Retention System

The lower airframe and fin can remained aerodynamically stable and impacted the ground with significant velocity. The impact shredded the forward section of the lower airframe, deformed the airbrakes around the forward closure, and buckled the motor casing.

Figure 13 Lower Airframe and Fin Can

4 Root Cause Analysis

A failure tree is one method used to identify the root cause of a failure. Construction of the failure tree begins with identifying the result of the failure, in this case the breakup of the vehicle. Each subsequent level of the tree describes direct causes of the result listed in the prior level. Items are categorized into three colors. Green indicates that the cause is closed, meaning that it was determined to not have occurred or to not have caused the failure. Orange indicates that the cause is unlikely, meaning that the investigation was unable to conclusively rule out this cause, but there is no significant supporting evidence or other reason to think the cause occurred. Red indicates the cause is open, meaning it has significant evidence in support of its occurrence and would cause the failures observed. Each level and cause in the failure tree are categorized with a number for easy identification.

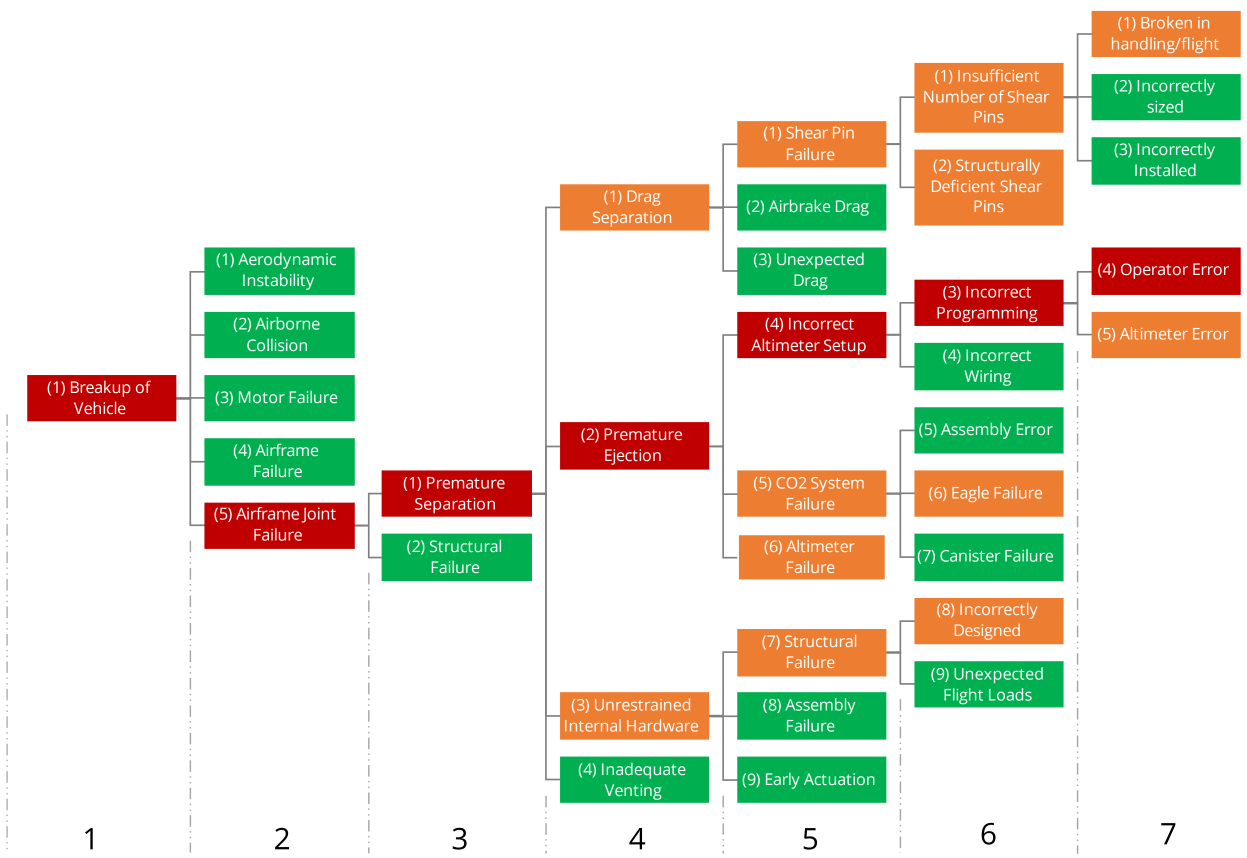

Figure 14 Failure Tree Diagram

A description of the cause, status, and supporting and opposing evidence for each cause is given in Table 1.

Table 1 Cause Summary Table

#	Description	Status	Supporting Evidence	Opposing Evidence
2.1	**Aerodynamic Instability** Aerodynamic instability could cause larger than expected structural loads and lead to breakup.	Closed	None	Photos and videos show the rocket flew straight without noticeable oscillation or instability. No damage was observed to aerodynamic surfaces.
2.2	**Airborne Collision** An airborne collision could cause structural failure and breakup of the vehicle.	Closed	None	No collision was observed in video or photos, and no damage was present that would indicate a collision.
2.3	**Motor Failure** Motor failure could compromise the structure of the vehicle, leading to breakup.	Closed	None	The motor casing was intact except for damage caused by ground impact. No evidence of motor failure during flight was observed. Flight data indicated nominal motor performance.
2.4	**Airframe Failure** Structural failure of the airframe or fins due to nominal flight forces could lead to breakup.	Closed	None	The only significant airframe damage was caused by ground impact.
2.5	**Airframe Joint Failure** Failure of the joints between airframe sections could lead to breakup.	Open	Photos and videos show the separation of the vehicle began at the nosecone joint.	None
3.1	**Premature Separation** Joint failure could be caused by premature separation, where the joint separates as intended but prior to the intended time.	Open	Photos and videos show the nosecone separated from the vehicle during flight.	None

#	Description	Status	Supporting Evidence	Opposing Evidence
3.2	**Structural Failure** Joint failure could be caused by structural failure due to expected or unexpected flight loads	Closed	None	Pictures and video of the failure show the nosecone joint separating cleanly. No damage was observed to the nosecone coupler.
4.1	**Drag Separation** A drag difference between the lower and upper sections could cause the joint to separate prematurely.	Unlikely	The nosecone separated from the vehicle during flight. Analysis of drag forces indicated that there was a separating force present.	The number of shear pins present should have been sufficient to prevent drag separation.
4.2	**Premature Ejection** Actuation of the CO2 ejection system could cause the joint to separate.	Open	Recovered altimeter data indicates the altimeter fired the ejection charge just before the nosecone separated	The ejection charge channel never lost continuity after firing the charge.
4.3	**Unrestrained Internal Hardware** Unrestrained hardware could move freely and cause separation by impacting internal components.	Unlikely	The forward section of the payload retention system was separated from the main retention system.	No evidence could be found conclusively proving if the retention system failed during boost or after the nosecone separated.
4.4	**Inadequate Venting** Inadequate venting could cause a pressure buildup in the airframe that could lead the joints to separate.	Closed	None	In the worst-case scenario, a fully sealed airframe would not generate enough force to come close to breaking even one shear pin.

#	Description	Status	Supporting Evidence	Opposing Evidence
5.1	**Shear Pin Failure** Issues with the shear pins could allow the nominal drag separation force to separate the joint.	Unlikely	The vehicle separated, when analysis showed the as-designed shear pins would be capable of handling nominal flight loads.	None
5.2	**Airbrake Drag** Actuation of the airbrakes could induce additional drag that can break the shear pins and separate the joint.	Closed	None	The airbrakes were not expected to have actuated before the breakup. Neither photos nor accelerometer data show the airbrakes deploying. With shear pins operating as designed, the airbrake actuation would not have caused a separation.
5.3	**Unexpected Drag** Unexpected additional drag due to fin flutter or other effects could increase the drag separation force above nominal values.	Closed	None	Acceleration data received from the telemetry system did not deviate significantly from the expected values until the failure.
5.4	**Incorrect Altimeter Setup** Incorrect programming on the altimeters could cause the altimeters to fire the ejection charges.	Open	Recovery of the altimeter settings indicates that the main channel of the Raven was set to fire the ejection charges at burnout.	The altimeter settings were recovered by Featherweight directly. They were unable to provide the tools used to decode the data, so this programming was unable to be independently verified.

#	Description	Status	Supporting Evidence	Opposing Evidence
5.5	**CO2 System Failure** Internal failure of the CO2 system could lead to the canister being punctured without a command from the altimeter.	Unlikely	The CO2 canister was punctured during flight.	No significant damage was observed when inspecting the CO2 system post-flight.
5.6	**Altimeter Failure** Altimeter failure could cause the ejection charges to fire prior to the programmed ejection conditions are met.	Unlikely	Investigation of flight data indicated that the altimeter sent power to the e-match.	The altimeters are commercial devices with a significant number of successful flights and no major known issues.
5.7	**Structural Failure** Structural failure of internal hardware could lead to loose components within the airframe that could move with enough energy to push the nosecone free.	Unlikely	The forward section of the payload retention system was separated from the main retention system.	There is no conclusive evidence proving the structural failure occurred prior to the breakup.
5.8	**Assembly Failure** Failure to properly assemble internal hardware could lead to unrestrained components within the airframe that could move with enough energy to push the nosecone free.	Closed	None	Closeout photos indicate that the payload was assembled as designed.
5.9	**Early Actuation** The payload retention system could be actuated to release the quadcopter. A released quadcopter could move with enough energy to push the nosecone free.	Closed	None	The payload electronics system was not active during flight, so could not have released the quadcopter early.
6.1	**Insufficient # of Shear Pins** If the number of shear pins were less than the required number, they could fail prematurely.	Unlikely	The vehicle separated under nominal flight loads based on accelerometer data.	Shear pin inspections prior to and after transport revealed no visible damage or missing pins.

#	Description	Status	Supporting Evidence	Opposing Evidence
6.2	**Structurally Deficient Shear Pins** A manufacturing defect or other effect could lead the shear pins to fail below their design load.	Unlikely	The vehicle separated under nominal flight loads based on accelerometer data.	No visible damage to any shear pins was observed before insertion. Other shear pins from the same batch had no issues.
6.3	**Incorrect Programming** Incorrect programming of the altimeter could result in the altimeter firing the ejection charge prior to the desired time.	Open	Recovery of the altimeter settings indicates that the main channel of the Raven was set to fire the ejection charges at burnout.	None
6.4	**Incorrect Wiring** Ejection charges wired to the incorrect channel could cause the charge to fire before it was intended to.	Closed	None	Closeout photos and records of altimeter beep codes indicate that the altimeters were wired as intended.
6.5	**Assembly Error** Incorrect assembly of the CO2 ejection system could lead to the system puncturing the CO2 canister prematurely.	Closed	None	Closeout photos and post-failure disassembly show that all CO2 systems were assembled correctly.
6.6	**Eagle Failure** Failure of the CO2 system could lead to the system puncturing the CO2 canister prematurely.	Unlikely	The CO2 canister was punctured during flight. The e-match did not lose continuity, suggesting it could have failed to fire.	The Eagle CO2 system is known to be reliable, and the team has not experienced nor heard of any prior premature ejections. Despite no loss of continuity, the e-match was visibly fired.

#	Description	Status	Supporting Evidence	Opposing Evidence
6.7	**Canister Failure** Over-pressurization due to excessive heating or other effects could lead to the canister failing during flight and releasing the CO2.	Closed	None	No damage was observed to the CO2 canister walls. The temperature within the vehicle remained below 120 F. Visual inspection revealed the punctures were made by the puncture piston, not over-pressurization.
6.8	**Incorrectly Designed** An incorrectly designed or manufactured component could lead to structural failure.	Unlikely	Poor manufacturing such as larger than expected chamfers in the groove could lead the snap ring to fail prematurely.	Post-flight analysis of the snap ring joint indicated it should be capable of withstanding tensile flight loads with a significant safety margin.
6.9	**Unexpected Flight Loads** Larger than expected flight loads could cause structural failure.	Closed	None	Acceleration data received from the telemetry system did not deviate significantly from the expected values until the failure.
7.1	**Broken in handling/flight** If one or many shear pins broke while handling and transporting the rocket or during boost the joint could separate under nominal loads.	Unlikely	The shear pins failed when they should have been capable of handling the observed flight loads.	Outside visual inspection prior to launch did not suggest the shear pins were damaged.
7.2	**Incorrectly Sized** If too few or too small shear pins were designed, the shear pins could fail under nominal flight loads.	Closed	None	The analysis of the number of require shear pins was reverified to be accurate.
7.3	**Incorrectly Installed** If the incorrect number of shear pins were installed the joint could fail under nominal flight loads.	Closed	None	Closeout photos indicate the correct number of shear pins were installed.

#	Description	Status	Supporting Evidence	Opposing Evidence
7.4	**Programming Error** If the operator entered the incorrect settings the altimeter would be configured incorrectly.	Open	The altimeter was programmed incorrectly. The settings were not reverified after they were noted to be incorrect during the first review.	The operator believes the altimeter was configured correctly.
7.5	**Altimeter Error** If the altimeter failed to save the programming entered it could be configured incorrectly.	Unlikely	The altimeter was programmed incorrectly.	No such failure mode has been observed with these altimeters. Operator error is the more likely explanation in this case.

The failure tree identifies a clear failure path, and some alternate failure modes that were possible, but unlikely. Each of the possible failure modes are discussed in more detail below

4.1 Drag Separation

Drag separation occurs due to a difference in drag between the forward and aft sections of the rocket. The fins and base drag at the rear contribute significantly to the total drag of the vehicle, while the nosecone is the only significant source of drag at the front of the vehicle. This difference in drag acts to separate the vehicle at its joints. The magnitude of the separation force can be calculated using Equation (1) [1].

$$F = \frac{M_t a}{(1+R) - M_l} \tag{1}$$

with:

M_t = Total Vehicle Mass (kg)

a = Maximum Deceleration (m/s^2)

R = Drag ratio $\left(\frac{C_{d_{upper}}}{C_{d_{lower}}}\right)$

M_l = Lower Section Mass (kg)

This equation accounts for inertial forces, where the difference in mass between the sections leads to either a separation force or a tension force at the joint, as well as aerodynamic forces which typically act to separate the vehicle.

From the parameters of our vehicle and flight data, the total separation force at the nosecone joint was 21.8 lbf (97 N). If the nosecone shear pins were not capable of withstanding this force, we would expect the joint to separate. The nosecone joint used three #4-40 shear pins, each generally capable of withstanding roughly 40 lbf (178 N) of shear [2]. Even a single shear pin therefore should have been sufficient to prevent drag separation. Closeout photos also indicated that the correct number of shear pins were used. Therefore, for drag separation to have occurred, the shear pins would have had to be damaged or weakened.

There was no conclusive evidence to prove or disprove the existence of structurally deficient shear pins, which would fail before the expected load, nor damage to the shear pins that occurred during transport or boost. However, both these explanations were ruled unlikely due to a lack of supporting evidence and stronger evidence for other explanations.

4.2 Unrestrained Internal Hardware

The vehicle contains various large and heavy internal components that must be rigidly attached to the main structure of the vehicle. If components were to break loose during flight, their motion could alter the stability of the vehicle, or their inertia could cause them to impact airframe joints and cause a separation. One of the earliest findings of the investigation was that the rotating section of the payload retention system had broken away from its attachment to the nosecone. The rotating section was connected to the nosecone via a single 3/8” aluminum shaft with a snap ring, necessary to allow the section to rotate independently.

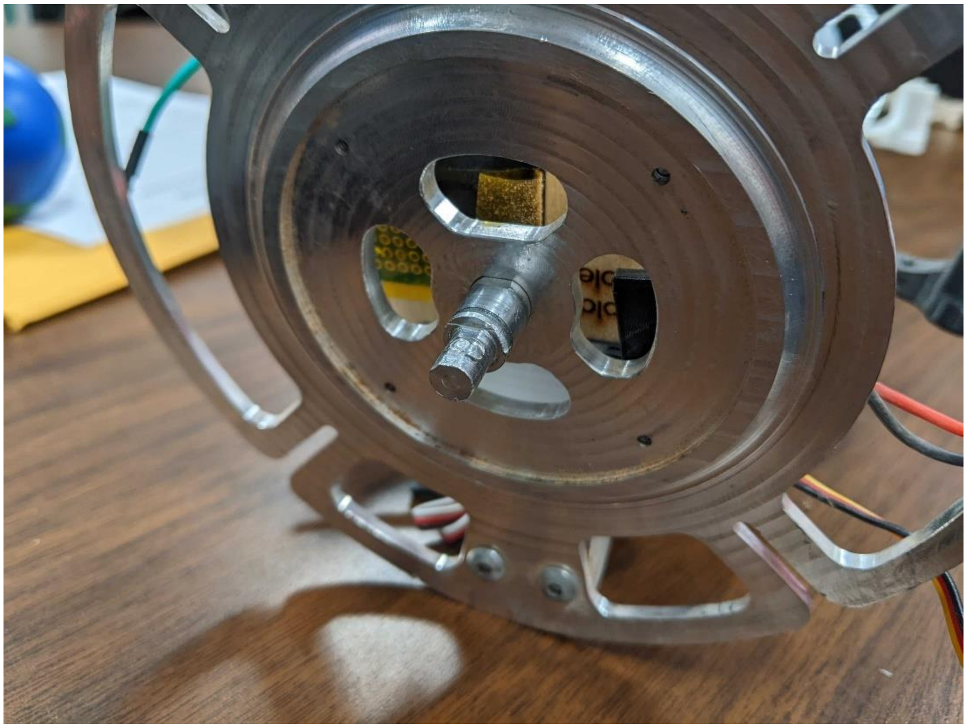

Figure 15 Rotation Shaft of Payload Retention System

Due to the weight of the section and the flight loads, it was theorized that the retention system could have broken away during boost, then its inertia could have carried it forward at burnout, impacting the nosecone with enough energy to cause the separation. This was a particular concern because retaining rings are rated for use with a shaft material harder than that of the ring. The aluminum 6061-T6 shaft is significantly softer than the 1060 steel retaining ring used.

To determine if the retaining ring was likely to have failed due to flight loads, a more detailed analysis of retaining ring loads was conducted using standard equations [3]. The constraining failure mode was determined to be due to groove deformation, with a theoretical load capacity of 541 lb (2406 N). The vehicle experienced a maximum acceleration of 7.5G during boost. The mass of the unrestrained section was around 5 lb, meaning the retaining ring would experience a maximum thrust load of 37.5 lbf (167 N).

While this analysis shows significant margin for failure due to thrust loads, it is possible that manufacturing inaccuracies could have resulted in a mis-sized groove, a chamfer, or other weakening feature so the failure mode could not be entirely ruled out. Additionally, when investigating the rotation shaft, some question was raised as to if the shaft would have survived the bending loads experienced during recovery. These bending loads were not present during flight as the payload assembly was contained within the airframe, but due to the parachute attachment location on the payload the shaft could have sustained significant additional loads that were not analyzed.

4.3 Premature Ejection

The vehicle utilizes CO_2 ejection systems to separate the nosecone at a predetermined altitude during descent. If this system was triggered during boost, it is likely that the airframe joints would separate. There are numerous reasons why the ejection system could have triggered prematurely.

It is possible that an altimeter failure such as a short circuit could result in power being supplied to the e-match against the programming of the altimeter, setting off the CO_2 system. The altimeters in question were damaged during impact, so it was impossible to determine if such an event occurred. However, we do know that these altimeters are commercial devices, with hundreds if not thousands of successful flights. It is therefore unlikely that an altimeter failure caused the separation.

It is also possible that the CO_2 system itself failed, puncturing the CO_2 canister without the e-match firing. This could happen due to unexpected flight loads, or mechanical failure. However, no unexpected loads were noted in the accelerometer data, and no obvious damage was present after disassembling the CO_2 systems. Again, these systems are commercial products, with many successful flights with more challenging dynamic environments, so it is unlikely that the CO_2 system itself failed. It is also possible that the CO_2 canister itself failed, however visual inspection of the canisters indicated a puncture hole consistent with those caused by the puncture piston of the CO_2 system, so this failure mode was ruled out.

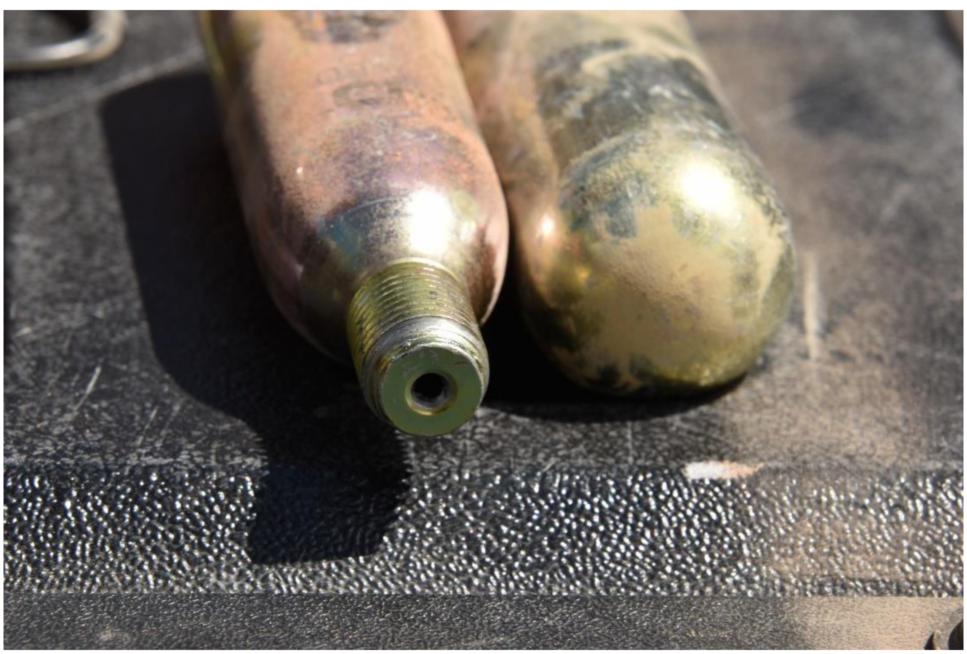

Figure 16 CO_2 Canister Post-Flight

The last remaining cause of a premature ejection is incorrect altimeter configuration. This could be due to wiring the ejection charge to the incorrect channel (i.e., to Apo instead of Main on the Raven 4), however closeout photos and post-flight inspection indicated that the e-matches were wired correctly. It is therefore likely that the altimeters were programmed incorrectly.

Post-flight inspection of the altimeter settings by Featherweight revealed that the Raven 4 altimeter used for backup payload deployment was configured to fire its main channel at motor burnout. The altimeter should have been configured to fire its ejection charge at 1300 ft during the descent of the vehicle.

The incorrect configuration could have been loaded on the altimeter due to a failure with the altimeter itself. To program the altimeter, the user enters the configuration using software provided by the manufacturer, then loads that configuration onto the altimeter. If the altimeter does not accept the programming, there may not be any indication to the user. This failure mode was deemed extremely unlikely, as the altimeters are commercial devices and are known to be extremely reliable.

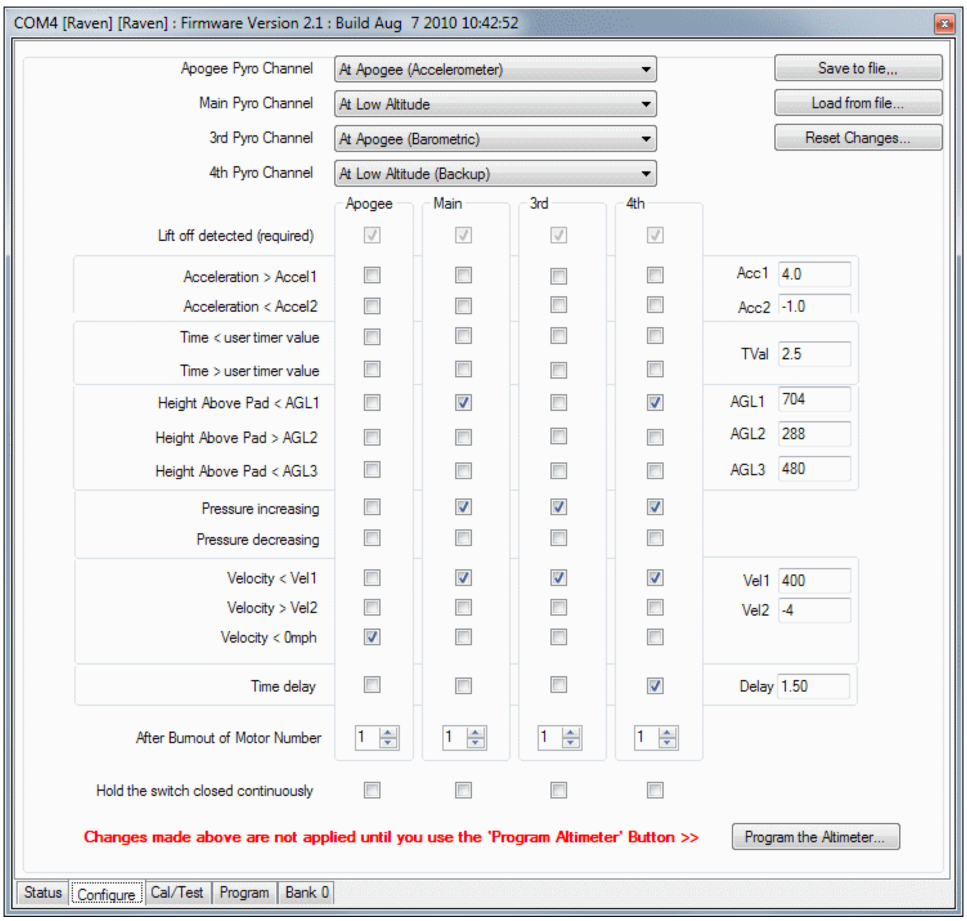

Figure 17 Example of FIP Interface

The most likely cause of the failure therefore is incorrect programming by the user. WPI HPRC follows a set of checklists during the setup and launch of the vehicle. One of the points on these checklists is to verify the payload altimeter settings prior to installation of the payload into the vehicle. During launch day, the altimeter settings for both the payload and rocket altimeters were presented for verification to the rocket division lead, and several issues were noted with the configuration of the altimeters. These issues were communicated to the member programming the altimeters, and the member was tasked with fixing the issues per the rocket division lead's verbal instructions. The member made, or believed they had made, the requested changes, and then the payload was integrated into the vehicle. At no point prior to integration were the settings reverified by any responsible parties. At this time, multiple events were occurring at once, and with only one checklist available the assembly of the vehicle proceeded without the proper signoff. Subsequently, the safety officer requested that the rocket lead verify that multiple checklist items relating to the recovery system had taken place, which the rocket lead confirmed. Among these items was the verification of the altimeter configuration.

The preceding description provides a clear path for the failure to have propagated along. This version of events is the agreed upon root cause of the breakup of the vehicle.

5 Conclusions and Recommendations

The cause of the in-flight failure of Altair at the 2022 Spaceport America Cup is determined to be an incorrectly programmed altimeter triggering the ejection system at burnout. This error has several contributing factors, primarily a failure to follow and properly document the completion of established checklists. Another contributing factor was the large number of tasks the division leads were responsible for overseeing on the day of launch, which took focus away from critical areas and regularly interrupted the process of verifying checklists. Additionally, proper altimeter settings were not documented anywhere easily available to the member tasked with programming the altimeters. Rather, the correct settings were only communicated verbally, and had not been reviewed with the member prior to the day of launch. Nor had the member been trained in detail on the operation of the altimeters, particularly the Raven 4 altimeter which has a more powerful, yet complicated programming interface.

The primary contributing factor, a failure to properly follow the established checklists, constitutes a failing of the executive and safety groups on the team. It should be noted that the executive and safety groups have consistently demonstrated their commitment to team safety in more direct settings, for instance choosing to conservatively scrub two launch attempts due to safety concerns in the 2021-2022 competition year, despite significant investment into those attempts. However, the leadership was complacent when it came to following the vehicle assembly and integration checklists, which did not pose an obvious direct hazard if something were to go wrong. This document should reinforce the importance of all safety procedures, even those that may seem insignificant, to WPI HPRC leadership, members, and to the rest of the collegiate rocketry community.

Based on this analysis, as well as experience gained from the team's first year competing at the Spaceport America Cup, the following recommendations have been developed to improve safety and success at future launches.

Table 2 Recommendations

#	Recommendation	Justification
1	Present these findings to the team, and incorporate the lessons learnt into a more comprehensive safety training that can be delivered to all new members in future years.	The major contributing factor to this failure was a failure to follow existing checklists. All members of the team should be made aware of the impact of seemingly insignificant shortcuts and oversights so that they may be avoided in the future.

#	Recommendation	Justification
2	Establish more rigorous verification methods for all checklist items.	Much of the verification of checklist items came down to asking a single individual if they had completed the task. Often, this responsibility lay with the division leads, who were extremely busy with various aspects of launch preparation and did not dedicate proper attention to all checklist items. A requirement to document proof of the completion of the task, such as via photo or video, printout, or even just the review of a second individual would encourage better adherence to the checklist and its verification.
3	Tailor checklists to be more specific and descriptive to the vehicle being launched, including a description of how to accomplish each check.	The checklists used by WPI HPRC are based on generic checklists developed in previous years that are then modified depending on the vehicle. Despite this, they still include unspecific language such as “verify altimeter programming” but give no guidance on how the verification should be completed or what values are meant to be loaded. Checklists should be vehicle unique and provide a clear process and expectation for verification.
4	Train members on the tasks they will be completing during launch day multiple times prior to launch.	Prior to a launch, there is currently no dry run process for members to familiarize themselves with the checklists. Members have been provided checklists to review but have never received hands-on training. The implementation of small-scale integration practice as well as large-scale dry runs would be beneficial to making sure members understand their roles and reduce the workload on leaderships on launch day.
5	Assign multiple safety representatives to handle different aspects of safety at launches.	WPI HPRC has one primary safety officer responsible for team safety. This officer can override all other members and leadership if they determine safety is at risk. However, the safety officer was responsible for all aspects of safety at IREC, from following checklists to ensuring members were applying sunscreen, eating and drinking. This variety of tasks would more properly be split between multiple safety representatives, allowing each representative to focus on a single task.

#	Recommendation	Justification
6	Verify COTS avionics programming by reading the data with a separate computer than the one it was programmed with.	From the point where the user presses “program”, the operation of an altimeter, GPS unit, or other COTS avionics system becomes a black box. While most programs will report a “success” or “failure”, there is no guarantee that the programming was loaded correctly. While failure to accept programming is unlikely, and was not the cause of this failure, verification with an independent system would provide an extra layer of security, both to hardware/software failure, and to human error by requiring the involvement of a second individual to verify this critical information.
7	Host more rigorous and regular inter-division design reviews	WPI HPRC consists of multiple divisions that work together throughout the year to develop our competition vehicle. The payload division works mostly independently of the rocket division, which is helpful, if not necessary from a management perspective, but also can contribute to poor communication and knowledge gaps. A rocket division member, more familiar with the loads and dynamics of recovery and landing under parachute may have identified the weakness in the rotation mechanism of the payload retention system. While this did not contribute to the failure this year, it is not difficult to imagine situations where expertise from one division would benefit the other. More regular inter-division reviews would increase the chances of identifying possible design issues and failure modes.
8	Investigate an improved method of installing, retaining, and protecting shear pins.	The shear pins are inserted into the vehicle prior to transport to the RSO and pad. Between this time and launch, there is the possibility that damage to the shear pins could occur, leading to drag separation or some other form early separation. Risk of damage to the shear pins is increased during installation since the holes they are installed into are relatively small to prevent the shear pins from coming loose during flight. It is not uncommon to break a shear pin during insertion. Improvements to the current system would reduce the risk of future shear pin failure.

#	Recommendation	Justification
9	Develop a checklist of closeout photos/angles necessary before the vehicle is deemed ready for launch.	While the number of closeout photos taken was sufficient to enable analysis of all necessary aspects of this failure, some findings required significant effort to verify due to information being spread across numerous unrelated photos. Additionally, the decision to take a given closeout photo was made in the moment. It is possible that in the future a critical piece of information could be unavailable because nobody was around or made the decision to take a photo. A standardized set of closeout photos would make future analyses much easier and reduce the risk of missing critical information.
10	Record absolute timing of logged data, photos, and videos more accurately.	During the investigation the task of aligning the various sources of data in time proved difficult. This was not critical for this investigation but could be in other investigations. While devices such as commercial altimeters will always require some effort to match to a real time value since they record relative times, avionics systems with GPS connectivity should be made to record absolute time, and cameras should be configured with the absolute time prior to launch or have a known accurate time source shown to them to sync the recordings.
11	Assign one or more static, wide view cameras to record the launch of the vehicle.	In the event of a failure with complete data loss, the only reference to determine vehicle performance may be through analysis of photos and videos. This analysis is complicated because most media of the event is taken from handheld cameras. To track the vehicle, you must first account for the movement of the camera, then the vehicle. While such analysis was not necessary for this failure, the team has had a failure in the past whose analysis would have benefited from a static camera, but this recommendation was neither developed nor implemented.

6 References

[1] Shear Pins on a 8" Dia Bird. *The Rocketry Forum*. https://www.rocketryforum.com/threads/shear-pins-on-a-8-dia-bird.153740/. Accessed Sep. 8, 2022.

[2] HPR Strength of Materials - Recovery Materials (Data). https://web.archive.org/web/20110811054310/https://www.rocketmaterials.org/datastore/cord/Shear_Pins/index.php. Accessed Sep. 8, 2022.

[3] Load Capacity. *Smalley*. https://www.smalley.com/ring-design/load-capacity. Accessed Sep. 8, 2022.