Development of a Smart Release Algorithm for Mid-Air Separation of Parachute Test Articles

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The Crew Exploration Vehicle Parachute Assembly System (CPAS) project is currently developing an autonomous method to separate a capsule-shaped parachute test vehicle from an air-drop platform for use in the test program to develop and validate the parachute system for the Orion spacecraft. The CPAS project seeks to perform air-drop tests of an Orion-like boilerplate capsule. Delivery of the boilerplate capsule to the test condition has proven to be a critical and complicated task. In the current concept, the boilerplate vehicle is extracted from an aircraft on top of a Type V pallet and then separated from the pallet in mid-air. The attitude of the vehicles at separation is critical to avoiding re-contact and successfully deploying the boilerplate into a heatshield-down orientation. Neither the pallet nor the boilerplate has an active control system. However, the attitude of the mated vehicle as a function of time is somewhat predictable. CPAS engineers have designed an avionics system to monitor the attitude of the mated vehicle as it is extracted from the aircraft and command a release when the desired conditions are met. The algorithm includes contingency capabilities designed to release the test vehicle before undesirable orientations occur. The algorithm was verified with simulation and ground testing. The pre-flight development and testing is discussed and limitations of ground testing are noted. The CPAS project performed a series of three drop tests as a proof-of-concept of the release technique. These tests helped to refine the attitude instrumentation and software algorithm to be used on future tests. The drop tests are described in detail and the evolution of the release system with each test is described.

I. Introduction

THE test program to design and validate the parachute recovery system for the NASA Crew Exploration Vehicle (CEV) includes ambitious objectives and complex test techniques.[5,6] This paper describes the development of one of these techniques. The CEV Parachute Assembly System (CPAS) development project desires to test the deployment and inflation of the parachute system under flight-like conditions in the wake of a representative forebody (or boilerplate capsule). Similar tests were performed on the Apollo program. However, the method used to deliver the Apollo boilerplate capsule to the test condition is infeasible due to the size of the Orion capsule and the available airframes.[7] CPAS has investigated an alternative technique that uses a modified Low Velocity Aerial Delivery (LVAD) system to extract a truncated boilerplate from a C-17 and deliver it to the test condition. The concept of operations for this technique will be described. Deployment of the boilerplate to the appropriate attitude required the development of a "Smart Release" algorithm. This algorithm will be defined and the test program to verify its utility will be described in detail.

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II. Boilerplate Test Concept of Operations

The full Orion outer mold line (OML) is incompatible with the available aircraft. For this reason, a Parachute Test Vehicle named PTV2 has been designed that maintains a representative diameter but has a truncated height. Figure 1 shows the difference between the Orion capsule and the test boilerplate. The height of the PTV2 has been reduced from 142 in. to 109 in. to allow extraction from a C-17. The parachute compartment of the PTV2 is representative of the actual Orion capsule. Prior to extraction from the aircraft the PTV sits on a custom extraction sled named the Cradle and Platform Separation System (CPSS). The CPSS is designed to interface with the aircraft and is also visible in Fig. 1.

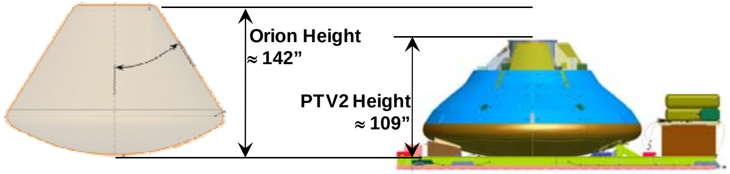


Figure 1. Comparison of Orion and PTV2 (from Ray and Morris[7]). *The PTV2 is a truncated Orion boilerplate capsule designed for extraction from a C-17 aircraft.*

Figure 2 is a schematic of a typical Concept of Operations (ConOps) for the planned PTV2 tests. The PTV2 is initially fixed to the CPSS. The mated PTV2 and CPSS are extracted from a C-17 at roughly 145 KIAS and 25,000 ft-above Mean Sea Level (MSL) using a modified LVAD technique. Shortly after extraction, the mated system passes through the desired separation attitude. This condition is sensed by the on-board avionics package which issues a command to cut the lashings that hold the PTV2 to the CPSS. The desired separation attitude will be described in the following section. The separation of the PTV2 from the CPSS extends a static line that deploys the PTV2 programmer parachute. This sequence is intended to deliver the PTV2 to the desired test condition in a heatshield forward attitude. The CPSS descends under a recovery parachute system that is deployed by static line when the extraction chute is cut away. The timing of the cut-away and sizing of the recovery system must be designed to maintain an acceptable distance from the PTV2 during descent while also keeping the touchdown footprint within an acceptable area.

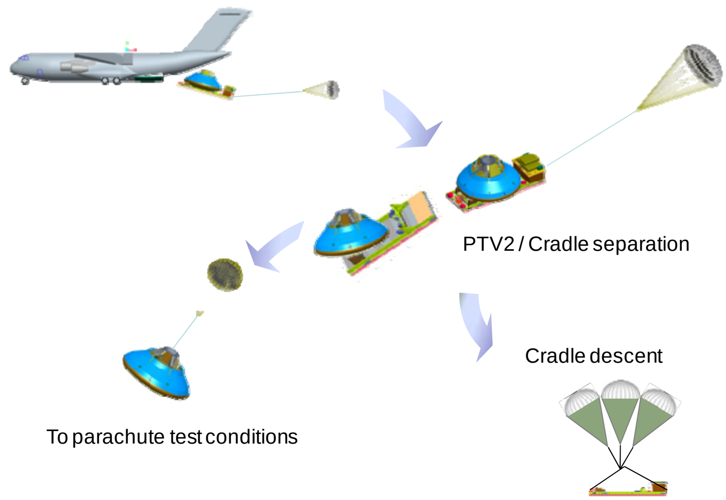


Figure 2. Concept of Operations for PTV2 tests (after Ray and Morris[7]). *The PTV2 is extracted from the aircraft atop the CPSS. Shortly after extraction, the two bodies separate and the PTV2 descends to the test condition under a static-line deployed programmer. The CPSS descends under its own recovery parachute system.*

The mid-air separation of the capsule shape from the platform is somewhat novel. The Apollo parachute test program had a customized aircraft that was capable of dropping the Apollo boilerplate in a heatshield down orientation directly from the rear of the aircraft. Other mid-air separation systems have had vehicles with active control systems or vehicle shapes that are more aerodynamically stable than the platform and capsule shapes.[7] Neither the PTV2 nor the CPSS will have an active control system. Fortunately, experience with delayed load transfer extractions has shown that the attitude motion upon extraction is predictable, at least in a qualitative sense. This indicates that the mated vehicle motion is repeatable. The next section describes an algorithm that CPAS has developed to identify when the mated vehicle achieves an attitude that is favorable for positive separation.

III. Description of the Smart Release Algorithm

The mid-air separation described above was previously attempted on the CPAS Cluster Development Test 2 (CDT-2). This test ended catastrophically due to cascading failures resulting from the collapse of the programmer parachute.[3] While the test condition was never achieved on CDT-2, a review of the extraction sequence determined that the separation attitude was unpredicted but desirable. Figure 4 shows the delivery of the CDT-2 boilerplate to the heatshield forward orientation upon separation from the CPSS. An accident investigation determined that the PTV wake and presence of stabilization parachutes contributed to the collapse of the programmer.[3] The CPAS project concluded that refinements to the separation sequence were required to avoid the programmer collapse and ensure that the motion observed on CDT-2 is repeated on future tests. Other refinements to the PTV2 outer mold line were applied to reduce snag hazards and improve the likelihood of successful parachute deployment.

Figure 3. CDT-2 Separation. *The previous attempt at a mid-air boilerplate/platform separation momentarily achieved the desired orientation.*

The motion of an LVAD pallet in a delayed load transfer extraction is fairly predictable if the center-of-gravity, mass, inertia tensor, and aerodynamics of the extracted pallet are known. During the first few seconds after extraction, most of the attitude motion occurs in the pitch plane. Extractions with a delayed Extraction Force Transfer Coupling (EFTC) release will typically exhibit a slight pitch-up as the pallet exits the aircraft ramp. This slight pitch-up is followed by a more dramatic pitch down and oscillation in the pitch plane. This behavior is depicted in the lower left-hand plot in Fig 4. The trajectory traces and numerical values in Fig. 4 are specific to the EDU-A-TSE-01 test series to be described below. The actual input parameters to the algorithm will depend upon PTV2 test trajectory predictions. Review of the CDT-2 test determined that the best time to separate the two bodies in order to repeat the CDT-2 separation is near the bottom of one of these pitch cycles. This occurs at the local minimum of the pitch angle and at the change in sign of the pitch rate from negative to positive.

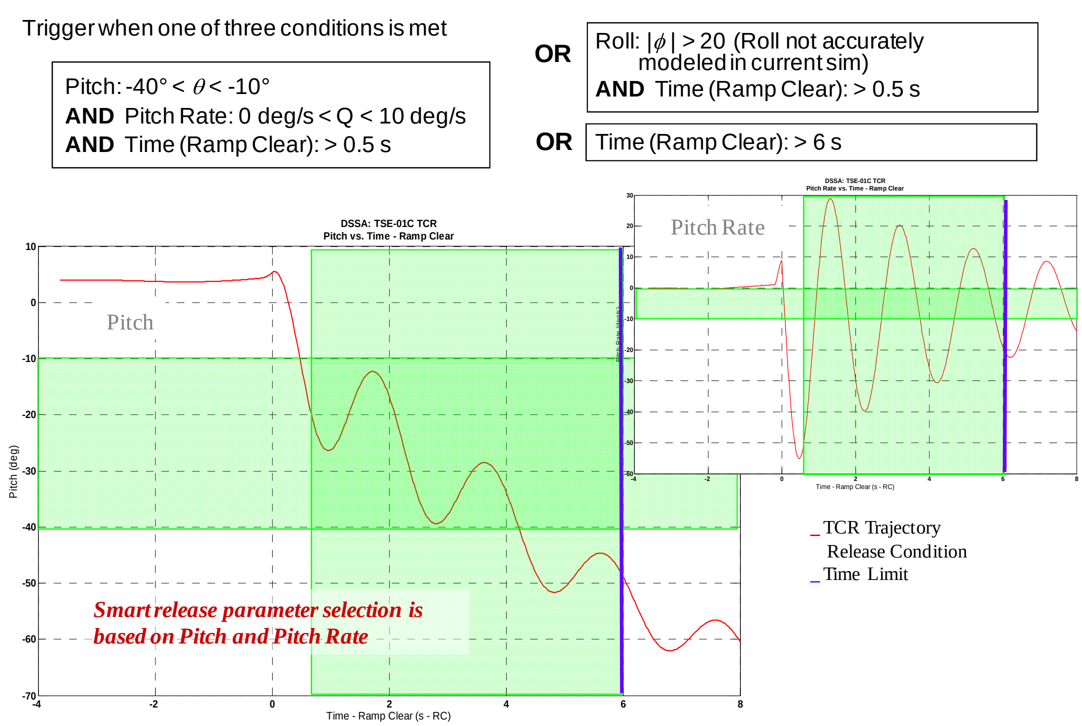


Figure 4. Smart Release Algorithm. *The Smart Release algorithm is designed to release the PTV2 when desired pitch and pitch rate conditions are met. Maximum time and allowable roll angle serve as back-up conditions to release the PTV2 if the optimum conditions are never observed. Numerical values in this figure are specific to the EDU-A-TSE-01 test series and may not apply to PTV2 tests.*

CPAS determined that the optimum release condition would be a function of the pitch angle and pitch rate. Therefore, CPAS engineers developed an algorithm to monitor the pitch and pitch rate of the mated PTV2/CPSS vehicle and identify the instant when both of these parameters are within acceptable limits. The pitch and pitch rate motion are sensitive to the mass properties and aerodynamics of the vehicle. Precise prediction of the motion requires high fidelity aerodynamic coefficients and accurate mass properties. Engineers anticipated the potential for test vehicles with various OMLs and mass properties. For this reason, the Smart Release algorithm was designed to allow flexibility in the selection of the acceptable pitch and pitch rate ranges.

A robust separation algorithm would also include contingency release conditions. Experience had shown that some delayed-EFTC-release extractions exhibited significant roll within a few seconds of extraction. A large roll angle would make it difficult to achieve the heatshield forward orientation. Therefore, the Smart Release algorithm includes a roll limit. If the roll angle exceeds the defined limit, then a release is inititated. The intent is to release the PTV2 before an undesirable roll angle is achieved, even if the pitch attitude is sub-optimal. A maximum time condition was included in the algorithm to ensure that separation occurred even if the optimal pitch attitude was never achieved. Finally, a minimum time is required to provide adequate distance from the aircraft before the PTV2 is released.

Pseudocode for the Smart Release algorithm is included below:

```
if time > minimum_time
   if (min_pitch < pitch < max_pitch) AND (min_pitch_rate < pitch_rate < max_pitch_rate)
      RELEASE
   else if (abs(roll) > max_roll)
      RELEASE
   else if (time > maximum_time)
      RELEASE
   end
end
```

where the max and min values are configured by the test team to achieve the desired release attitude. The Smart Release algorithm described above provides versatility in defining the desired release orientation and is robust enough to ensure release if the actual extraction dynamics are off-nominal.

IV. Testing the Smart Release Algorithm

The algorithm described above was tested in three ways. The software algorithm was coded in MATLAB and used to process both flight data and simulation data. The algorithm was coded into the avionics system and ground tested with a set of programmed test inputs (PTIs) and a library of simulated trajectories. Finally, a series of three drop tests were performed that included primary objectives aimed to test the CPAS Generation II avionics system including the Smart Release algorithm.

A. Testing of a Software Implementation of the Smart Release Algorithm

The first step in the algorithm testing was a proof-of-concept phase intended to verify the utility of the algorithm. A MATLAB version of the Smart Release logic was coded and used to post-process data collected on previous drop tests. The algorithm was successfully able to identify the targeted minimum pitch angle by monitoring the recorded pitch and pitch rate histories. The testing evaluated multiple values of the user-configurable limits on pitch, pitch rate, roll, and time with flight data from multiple Generation I CPAS tests. At this stage of testing CPAS engineers observed that, for some tests, the pitch rate data was much noisier than the pitch data. This raised a concern that the algorithm might fail to correctly detect when the desired orientation had been reached because the instantaneous pitch rate data was unreliable. This phenomenon was pronounced on tests involving the separation of a dart-shaped vehicle from a cradle-monorail pallet. Historically, pallet and weight-tub drop tests had shown only modest noise in the pitch rate channel. Since the noise characteristics of the eventual boilerplate/pallet configuration were not understood, the project decided to add a filter to the pitch rate channel to smooth the data prior to processing with the algorithm. Figure 5 shows an example of one of these tests and the effect of the filter on removing the false-detection of the release orientation. This test was designed to detect the initial peak in pitch using pitch limits of 0° and 20° and pitch rate limits of 0°/s and -0.5°/s. Roll and time limits were selected so that they would not be a factor in the detection. Figures 5b and 5d show the noise in the pitch rate channel and how it might lead to a false trigger condition near 1.1 s. The filtered data was more reliable in detecting the actual peak pitch at 2.2 s.

Additional testing was performed on simulation data. This type of testing served two functions. The first was to test the Smart Release algorithm with a wider variety of attitude histories than were available in the existing flight data. Extraction trajectories were generated with the Decelerator System Simulation Application (DSSA).[1,2]

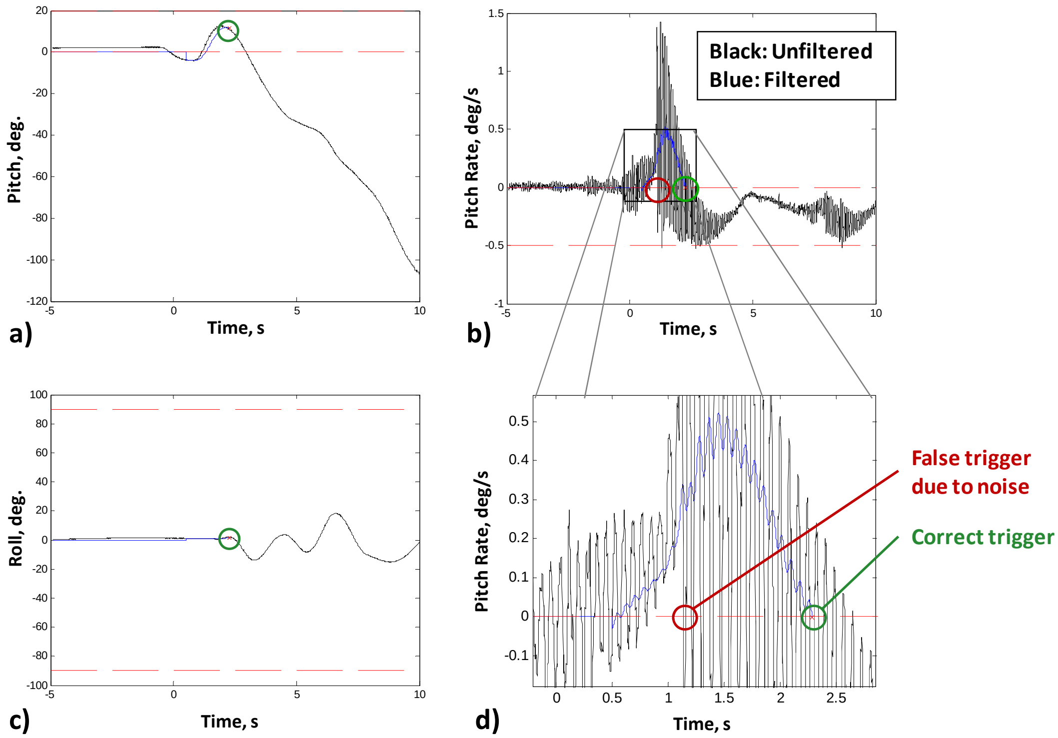


Figure 5. Smart Release testing on previous flight data. *The Smart Release algorithm was applied to recorded flight data to test the functionality on test-like data. Noise in the pitch rate data can create false trigger conditions. (After an unpublished figure by Kristin Bledsoe of the Engineering & Science Contract Group.)*

No noise was modeled in the simulation data. However, simulations were useful for creating extreme cases that were not present in the available test data.

A second purpose for performing the simulation tests was to verify the accuracy of the MATLAB implementation of the Smart Release logic. The planned drop tests required 6-Degree-of-Freedom simulation in DSSA for prediction of test trajectories. A Monte Carlo analysis of the test trajectories was performed due to uncertainty in many of the test parameters. The MATLAB version of the release logic was included in the CPAS analysis Monte Carlo tool[4] so that the Smart Release condition could be evaluated on the dispersed extraction attitude histories. The Monte Carlo trajectories were useful in confirming an appropriate range for the Smart Release logic inputs. The limits on pitch, pitch rate, roll, and time were required to be broad enough to ensure that the trigger condition was satisfied during the actual flight but not so broad that the logic triggered before the desired condition was met. Figure 6 shows the Monte Carlo DSSA pitch and pitch rate results. The release point of each dispersed cycle is plotted as a small circle on the pitch and pitch rate histories. The grouping of the release points shows that every dispersed cycle released at the desired event, namely, the minimum of the first pitch cycle using pitch limits of -10° to -40° and pitch rate limits of 0° to 10°.

The results of these tests confirmed that the Smart Release algorithm was sound. CPAS engineers performed additional testing to verify the implementation of the algorithm in the avionics system and its performance when processing actual data from the flight sensors.

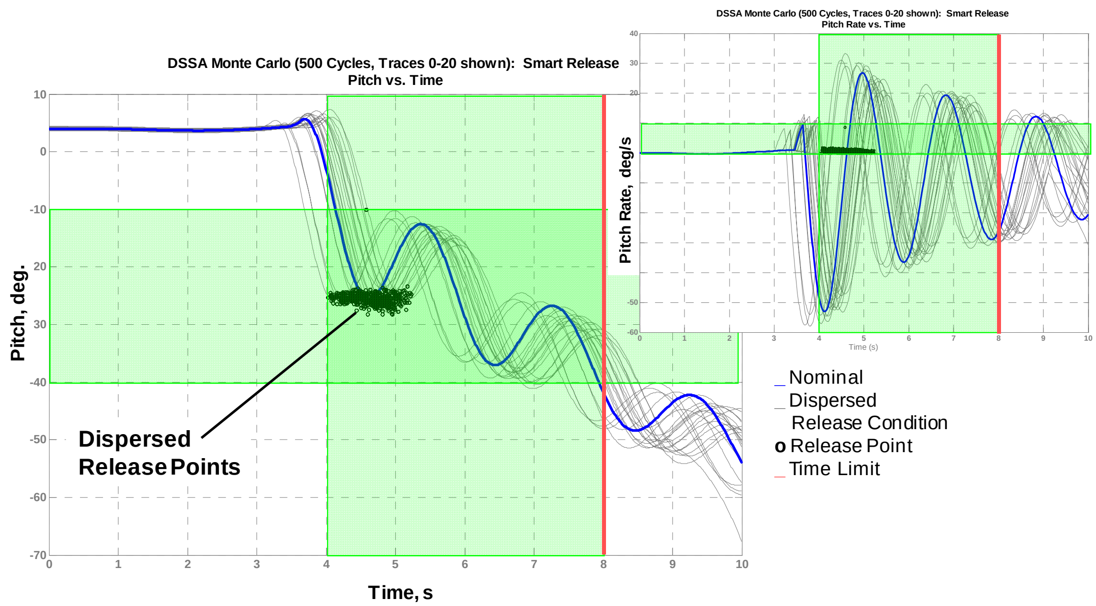


Figure 6. Smart Release with Monte Carlo simulation. *Appropriate pitch and pitch rate limits were determined through Monte Carlo analysis. Here all dispersed trajectories triggered the Smart Release logic at the same trajectory event.*

B. Ground Testing of the Avionics Implementation of the Smart Release Algorithm

The Generation II CPAS Avionics system includes a National Instruments Compact Reconfigurable Input/Output (CRIO) Field Programmable Gate Array (FPGA) controller. A Microstrain 3DM-GX1 orientation sensor was initially chosen as the source for attitude data. The avionics system included a redundant set of sensors and controllers. The Smart Release algorithm was coded in the avionics controller and tested with manual PTIs and by feeding flight data and simulation data through the avionics system. This phase of testing was not as extensive as originally planned due to time constraints and other priorities in developing the Generation II CPAS avionics package. A post-flight review of the first drop test uncovered implementation issues and additional ground testing with the flight hardware was performed.

The Smart Release algorithm as coded in the CRIO controller was tested by feeding artificial flight data through the avionics. This data included previous flight data, simulation data, and specially designed test input data files. This artificial data was intended to provide a wide variety of possible orientation histories. This was similar to the approach taken with the MATLAB implementation. Trigger limits could also be tailored for simulated data in order to test each possible path through the logic. The specially designed input data files were created to investigate the behavior of the Smart Release logic at the various gates in the logic path. For example, the Smart Release logic might evaluate whether a given parameter is strictly less than a limiting value. These special inputs data files were used to verify the expected behavior of the logic when the test parameter was exactly equal to the limiting value. Using these artificial orientation histories, it was possible to test every possible path through the Smart Release logic. Engineers evaluated the performance of the CRIO implementation of the algorithm by manually verifying that the test triggers occurred when expected (based on the custom orientation histories) and by comparing the results with trigger times determined by the MATLAB implementation of the algorithm.

Physical testing was conducted by fixing the orientation sensors to a platform that could be maneuvered to various orientations. The intent of this phase of testing was to verify acceptable performance of the Smart Release algorithm with data collected from the sensors to be used in flight. This type of hardware-in-the-loop testing can identify unanticipated issues with sensor interfaces and data processing. The algorithm testing with the flight hardware provided confidence that the system would perform as planned in the upcoming drop tests.

C. Flight testing of the Smart Release Algorithm

The algorithm verification and ground testing described above indicated that the Smart Release logic was ready for testing in flight. The CPAS project performed a series of three drop tests with the goal of verifying the effectiveness of the Smart Release system for use on a PTV2/CPSS test. The three tests were designed to test the Generation II CPAS avionics system by progressively increasing the responsibility of the new system in performing the test sequencing. An additional and equally valued test objective was the collection of rate-of-descent data for two CPAS Main parachutes. The initial portion of the test was intended to simulate the PTV2/CPSS ConOps. None of the tests planned for the actual mid-air separation of two bodies. Instead, a Type V LVAD pallet was outfitted with a weight tub and honeycomb structure that roughly mimicked the mass and aerodynamics of a mated PTV2/CPSS vehicle. The Smart Release firing command activated a set of flash bulbs instead of initiating a pyro-mechanical cutter as is anticipated with the PTV2/CPSS. Figure 7 is a schematic of a typical EDU-A-TSE-01 series test. Each of the tests used the test vehicle described above. The vehicle was extracted from a C-130A aircraft at roughly 20,000 ft-MSL. In the PTV2/CPSS ConOps the vehicles are expected to separate shortly after extraction,

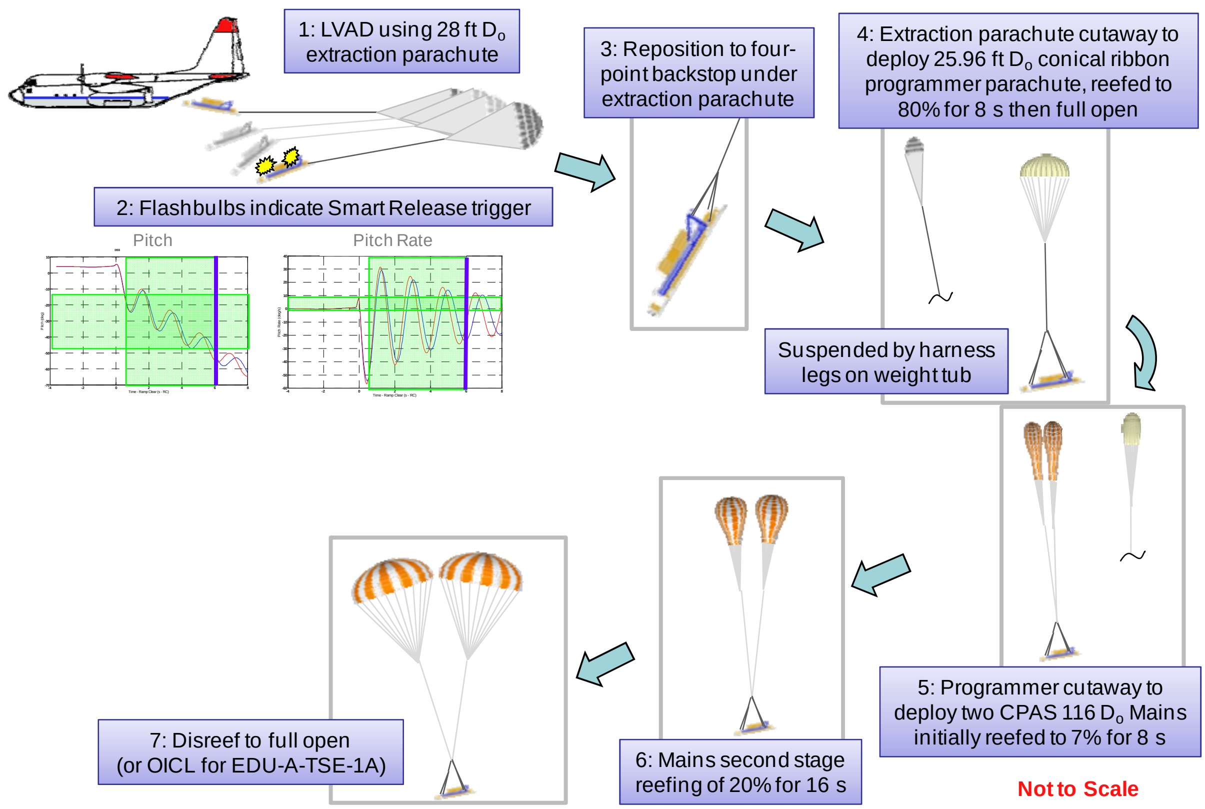


Figure 7. Smart Release air drop test schematic. *Three drop tests were performed to verify the performance of the Smart Release logic and collect data on the CPAS Main parachutes. No vehicle separation was planned for these tests. The avionics system fired flash bulbs when the target orientation was achieved.*

while the CPSS is still attached to the extraction parachute. In the EDU-A-TSE-01 series, flash bulbs were fired by the Generation II avionics system when the Smart Release condition was detected. After approximately ten seconds, the extraction parachute repositioned to four attach-points on the rear of the test vehicle to orient the test article for a smooth transition to the programmer parachute. Roughly 30 seconds after exiting the aircraft, the extraction parachute was cut away and a 26-ft programmer was deployed to achieve a dynamic pressure of roughly 50 psf at deployment of the test parachutes. Sixty seconds after exiting the aircraft, the programmer was cut away and two CPAS Main parachutes were deployed and inflated through two reefed stages to the full open configuration. The three EDU-A-TSE-01 tests followed the same Concept of Operations with minor adjustments to the release altitude to manage touchdown footprint in response to test day winds. The results of the three EDU-A-TSE-01 tests will be described in sequence.

1. Test EDU-A-TSE-01A

EDU-A-TSE-01A was conducted on October 2nd, 2009 at the Yuma Proving Grounds (YPG), Arizona. The test vehicle was extracted from a C-130A aircraft at an altitude of 21,574 ft-MSL and a true airspeed of 342 ft/s. The programmer parachute deployed and inflated successfully. The CPAS Mains exhibited nominal deployment and inflation. Descent under the Main parachutes was as expected.

While the test executed as planned, review of the data revealed that additional work was needed to mature the avionics system to the desired level of fidelity. This was the first flight of the Generation II system and the need for refinements was not unexpected. The test data revealed three primary problems that affected Smart Release performance:

1) There was significant disagreement in the measurements and trigger times recorded by the redundant systems.
2) There was notable lag between the occurrence of the desired orientation and the recognition of the condition by the avionics system and the issuance of the firing command.
3) The system erroneously processed filtered roll rate instead of filtered pitch rate.

Item 3 was the easiest to fix. Figure 8 depicts the time history of the Smart Release inputs and output for both systems. The difference in the recorded pitch angles between the two systems is visible. The test data was processed

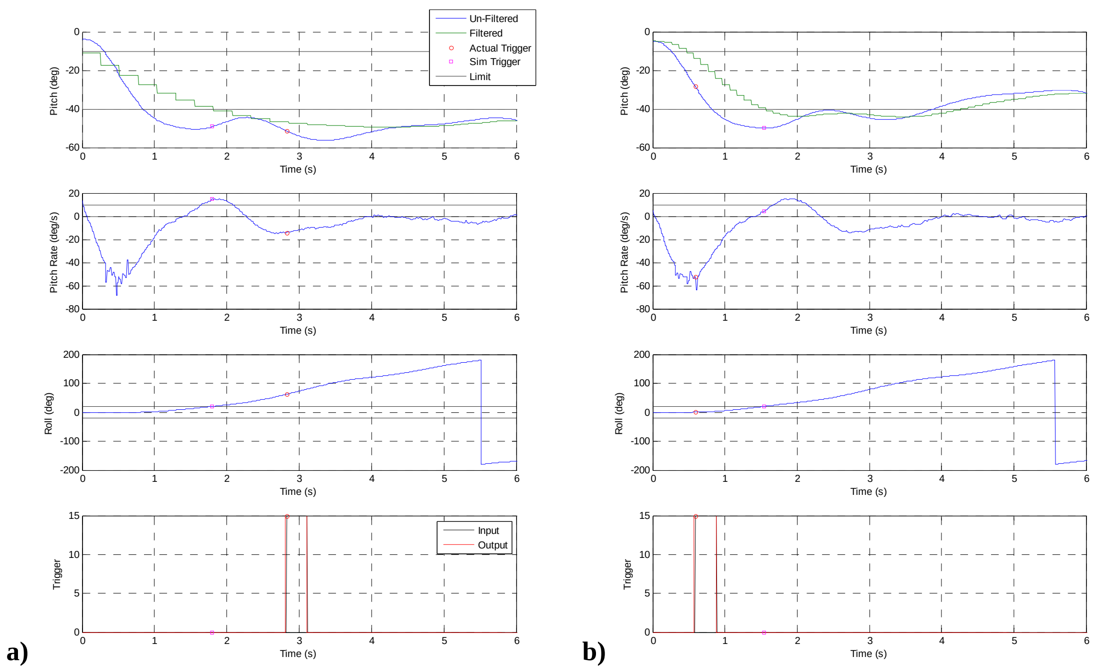
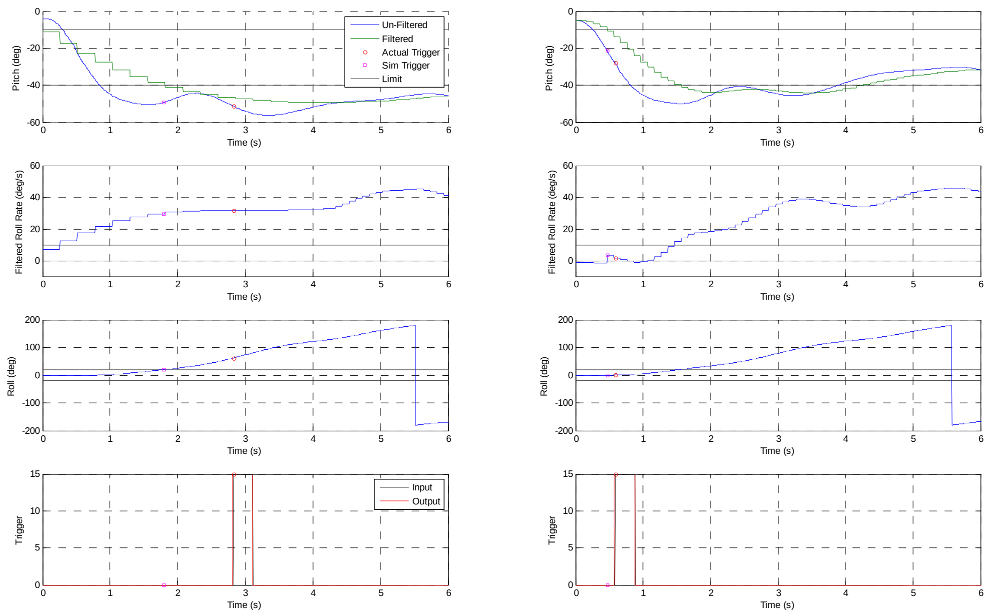


Figure 8. EDU-A-TSE-01A Smart Release performance assessment [FIGURE TO BE REDRAWN PRIOR TO PUBLICATION]. *The input orientation measurements recorded by the two systems differ considerably. Each system detected the Smart Release condition at a different time.*

with the MATLAB version of the Smart Release logic for comparison. Since each system received different orientation data, the MATLAB Smart Release logic detected the release condition at a different time on each system. It should be noted that the two systems were designed to be identical, with independent sensors located in the same location and in the same orientation. In Fig. 8 it is clear that the actual trigger times do not agree with the MATLAB detected trigger conditions. Moreover, it is not clear from the data traces which test condition caused each system to trigger. The orientation sensor provided a variety of available output data packages. The generic names of the output variables, 'X-rate', 'Y-rate', and 'Z-rate' were misinterpreted when translated to Euler angle rates. The interpretation also depended on the orientation in which the sensor was mounted on the test vehicle. The size of the test vehicle made it impractical to perform hardware-in-the-loop testing of the vehicle after sensors were mounted and connected to the data collection system. This problem was corrected with a simple software modification.

The other issues were more difficult to diagnose and correct. To further assess the performance, the error described above was duplicated in the MATLAB logic to determine if the system performed as expected given that it was processing roll rate data instead of pitch rate data. Figure 9 was used to evaluate the performance of the Smart Release system under these assumptions. In Fig 9a, the MATLAB logic determined that the pitch and roll-rate values did not simultaneously satisfy the pitch and pitch-rate conditions so the system should have triggered when



a) b)

Figure 9. EDU-A-TSE-01A Smart Release MATLAB reconstruction [FIGURE TO BE REDRAWN PRIOR TO PUBLICATION]. *System A does not appear to trigger at the appropriate time. Each system detected the Smart Release condition at a different time.*

the roll limit was exceeded at roughly 1.7 s. However, it is clear that the system did not actually trigger until roughly one second later. Figure 9b shows that the B-system sensors gave measurements that momentarily satisfied the pitch and pitch-rate limits. However, MATLAB detected the desired condition at 0.47 s and the flight system did not detect it until 0.59 s. The system A error was tracked to a problem with the data logging rate and lagging performance of an internal error checking routine. The system B problem was tracked to an inadequate filter processing rate. These issues may not have been uncovered during pre-flight testing because this testing focused specifically on the smart release logic and only a subset of the data logging tasks were performed.

These problems were addressed by optimizing the data logging rate and logic testing frequencies of the FPGA. The CPAS avionics and analysis teams agreed on a set of minimum synchronization and trigger requirements that were adequate for collecting data for extremely short duration testing events (such as drogue inflations) while not so stringent as to over-burden the avionics controller. Those requirements were:

1) The time elapsed between the achievement of the Smart Release condition and the firing command shall be less than or equal to 0.02 s.
2) The sensors on a single avionics string shall be synchronized to within 0.01 s.
3) The redundant avionics strings shall be synchronized with each other to within 0.1 s.

The final problem to resolve was the disagreement in the basic input measurements between the two systems. Because the roll measurement and the angular rates agreed between the two systems, but the yaw and pitch angles did not, the CPAS analysts suspected a possible problem with the kinematic integration of the Euler angles. The yaw angle from the orientation sensor was determined with a magnetometer. The test vehicle contained a large amount of ferrous metal and was subject to varying electromagnetic environments as it was extracted from the aircraft. It seemed quite possible that any initial difference in the yaw angle measured by the two sensors would propagate through the pitch angle as the angular rates were integrated within the sensor. For the second test, the CPAS avionics and analysis teams decided to place the orientation sensor in vertical gyro mode in an attempt to isolate the pitch and roll readings from the yaw measurement. The avionics system was configured to record a set of Crossbow Nav440 GPS/IMU units to provide an independent source of orientation data. In addition to these sources, a Novatel SPAN-SE GPS/IMU system was mounted on the test vehicle for each test. This instrument package requires post-processing and is not suitable for real-time attitude determination. This was a unique application of the SPAN-SE and the post-processed data was not available to support decisions prior to the second test. Finally, the avionics software was modified to log the state of each of the tests in the Smart Release logic. This addition to the data set allowed engineers to compare the state of the logic against the recorded orientation data and determine why the logic did or did not trigger.

Additional and more extensive ground testing of the avionics system was performed both at the Johnson Space Center and on the actual test vehicle in Yuma. This testing was similar to the ground testing described above but was performed while the full system was operating and recording all channels. Recorded flight data, sim data, and artificial PTI data were processed by the Smart Release logic and results were evaluated against the time accuracy and synchronization requirements described above.

Engineers attempted to mimic the orientation history provided by the sensors during live tests by manually manipulating an orientation sensor assembly. It was not possible to completely imitate the orientations and accelerations of the test vehicle with the available test hardware. The second round of ground testing showed significant improvement to the entire avionics system and to the Smart Release logic performance. Concern over the performance of the orientation sensors themselves lingered. However, the improvements witnessed in the ground testing had improved confidence in the data acquisition system. The desire to collect data for the other test objective (CPAS Main rate-of-descent performance) and the potential loss of test range availability compelled the project to proceed with the second test. A re-test of the system with the additional orientation sensors included for comparison would provide the data needed to resolve the sensor issue.

2. Test EDU-A-TSE-01B

EDU-A-TSE-01B was conducted on December 1st, 2009 at the Yuma Proving Grounds (YPG), Arizona. The test vehicle was extracted from a C-130A aircraft at an altitude of 21,175 ft above Mean Sea Level (MSL) and a true airspeed of 321 ft/s. The programmer parachute deployed and inflated successfully. The CPAS Mains exhibited nominal deployment and inflation. Descent under the Main parachutes was as expected.

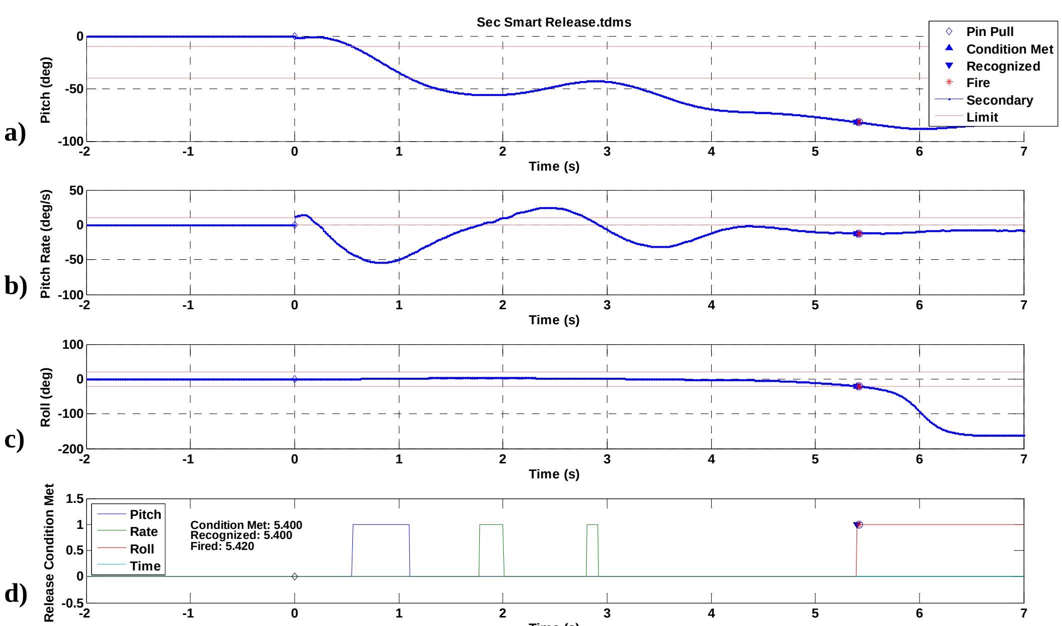


Figure 10. EDU-A-TSE-01B Smart Release performance assessment [FIGURE TO BE REDRAWN PRIOR TO PUBLICATION]. *System B triggers as expected. However, the orientation data was found to be erroneous.*

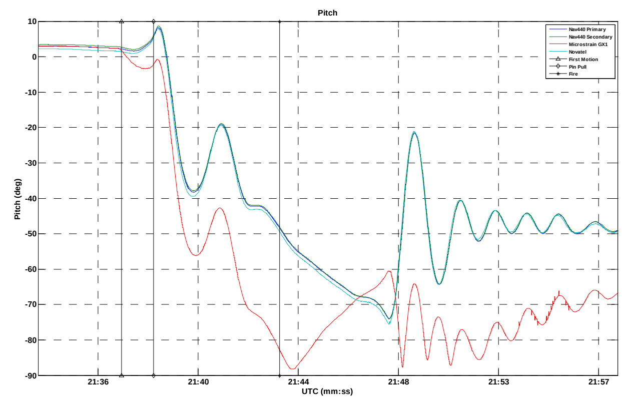
Performance of the Generation II avionics system was notably improved over test EDU-A-TSE-01A, but additional challenges remained. With regard to the Smart Release objectives, there were two important issues:

1) System A did not perform as expected due to a voltage drop-out.
2) System B did not trigger at the desired attitude.

This first problem affected the entire A-string of the avionics system and was not related to Smart Release. This problem was a hardware issue that was resolved prior to additional testing. The second problem was traced to the orientation sensor. The Smart Release logic itself performed as expected on this test. Figures 10a, 10b, and 10c show the pitch, pitch rate, and roll histories for the first seven seconds of the test. Figure 10d shows the logic state flags that were added to the avionics after test EDU-A-TSE-01A. The logic performed as would be expected given the orientation data and triggered on an excessive roll angle at 5.42 s. The pitch and pitch rate conditions were not simultaneously met prior to the time that roll exceeded its limit. However, the large roll angle was not observed on the test video.

The orientation from the GX-1 sensor was compared against that of the Nav440 sensor and the Novatel SPAN-SE. The GX-1 was found to disagree considerably in the pitch channel from the Nav440 and the SPAN-SE. Figure 11a shows a comparison of the pitch histories. The GX-1 shows a non-physical pitch down of the test vehicle before it exits the aircraft ramp. The difference in pitch angle grows to about 40° within a few seconds and eventually returns to agreement with the other sources. A similar disagreement was observed in the roll data. Curiously, the angular rate data agreed well with the other data sources. To investigate the problem, the angular rates were integrated independently using the appropriate kinematic equations of motion. The result is shown in Fig. 11b. The integrated angle agreed fairly well with the Euler angles measured by the Nav440 and SPAN-SE, at least for the initial motion. The agreement of the other orientation sensors and the integrated rates led the CPAS analysts to believe that the GX-1 sensor was unreliable in this application. The GX-1 output mode employed in these tests utilized an internal algorithm that was meant to filter out transient linear accelerations. After additional ground testing, the avionics and analysis teams reached a consensus that the strong longitudinal acceleration associated with the extraction event overwhelmed this filter or caused the filter to overcompensate for the short onset acceleration.

a)



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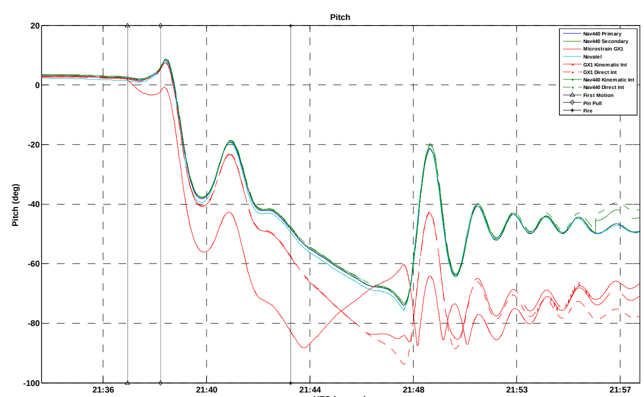

Figure 11. EDU-A-TSE-01B Pitch behavior after extraction [FIGURE TO BE REDRAWN PRIOR TO PUBLICATION]. *The GX-1 sensor disagrees considerably with the other sources of pitch data. Integrating the GX-1 rates provided more reasonable results.*

The agreement of the Nav440 and SPAN-SE sensors suggested that there might be an effective alternative to the GX-1. The SPAN-SE is not suitable for real-time processing. Other solutions that were investigated included, determining an alternate data package from the GX-1 suite, modifying the internal GX-1 filter settings, and independently integrating the GX-1 angular rates in real-time within the Smart Release algorithm. Ultimately, the CPAS project decided to replace the GX-1 units with the Nav440 units as the source for Smart Release orientation data.

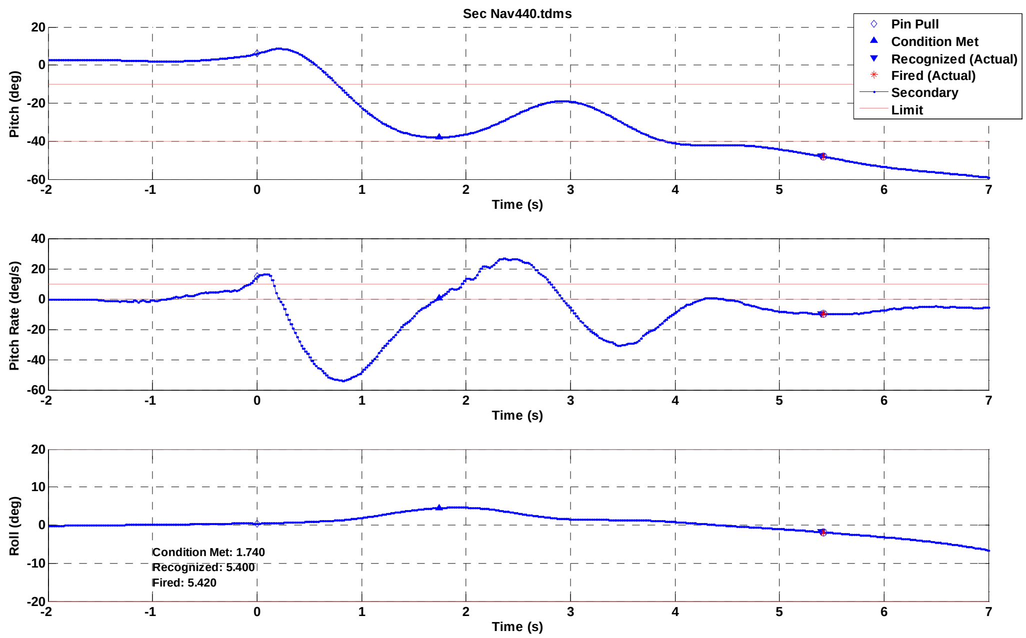

Figure 12. EDU-A-TSE-01B Smart Release performance assuming Nav440 inputs [FIGURE TO BE REDRAWN PRIOR TO PUBLICATION]. *The post-flight application of the Smart Release algorithm to the EDU-A-TSE-01B Nav440 data indicates that the Smart Release logic would have triggered at the appropriate attitude.*

The EDU-A-TSE-01B data collected from the Nav440 was processed with the MATLAB Smart Release implementation. Figure 12 shows the pitch, pitch rate, and roll histories. The MATLAB analysis indicated that the Smart Release would have been triggered at the desired point near the minimum of the first pitch-down. The desired pitch and pitch rate conditions occurred simultaneously at roughly 1.7 seconds and an excessive roll angle was not observed. This result also agreed well with the pre-flight predictions of the extraction and Smart Release trigger.

3. Test EDU-A-TSE-01C

EDU-A-TSE-01C was conducted on February 9th, 2010 at the Yuma Proving Grounds (YPG), Arizona. The test vehicle was extracted from a C-130A aircraft at an altitude of 20,528 ft above Mean Sea Level (MSL) and a true airspeed of 334 ft/s. Unfortunately, the EFTC device failed to release, which in-turn prevented the deployment of the programmer and CPAS Main parachutes. The test vehicle crash landed under the extraction parachute. The avionics system was destroyed. Remarkably, CPAS engineers were able to recover a few seconds of data from the storage device. The EFTC release is a mechanical process and is not activated by the avionics system. Test video indicates that the avionics system was operational during the test. Four flashbulbs were mounted on the test vehicle and were commanded to fire by the avionics system when the smart release conditions were satisfied. Figure 13 shows the firing of these flash bulbs at 1.46 seconds after the vehicle clears the aircraft ramp.

Figure 13. EDU-A-TSE-01C Smart Release trigger. *Four flash bulbs mounted on the test vehicle were fired by the avionics system when the release condition was sensed.*

Fortunately, the portion of the test data that was recovered includes the first few seconds of the drop test. This is sufficient to assess the performance of the refined Smart Release logic. Figure 14 shows the

Nav440 sensed pitch, pitch rate, and roll measurements. The smart release logic indicators added to the avionics system after test EDU-A-TSE-01A indicate that the avionics system recognized satisfactory pitch and pitch rate conditions at 1.41 seconds after clearing the aircraft ramp. This event and the flashbulb fire are indicated on Fig. 14. Also indicated is the MATLAB solution for trigger time. These events coincide with the minimum pitch down observed in the data. Currently available data does not allow complete synchronization of the aircraft video ramp clear event with the pin-pull event that is recorded by the avionics system at ramp clear. This information would allow further synchronization of the flash bulb fire (based on video) with the Smart Release command (based on avionics data). Nevertheless, Fig. 14 suggests that the Smart Release logic performed successfully on test EDU-A-TSE-01C.

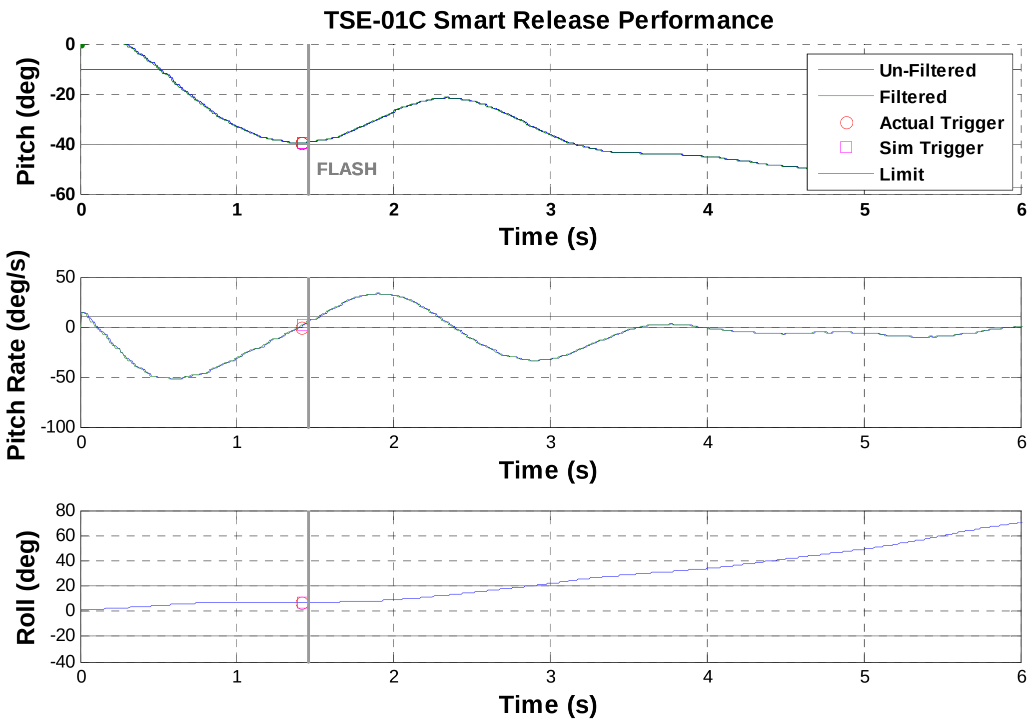

Figure 14. EDU-A-TSE-01C Smart Release Performance. *Evaluation of the recovered EDU-A-TSE-01C data indicates successful performance of the Smart Release logic.*

The EDU-A-TSE-01 series were a test technique and avionics development project that included several engineering challenges. While not all of the test objectives were achieved, the Smart Release algorithm was demonstrated to perform as expected by the final test. Additional confidence in the system may be gained by passively executing the release logic on future pallet-like tests that are planned before the PTV2 test series.

V. Conclusion

The Smart Release algorithm developed by CPAS is intended to be employed on the PTV2 boilerplate tests to verify the performance of the Orion parachute system. The size of the Orion capsule and limited availability of modifiable aircraft lead the CPAS project to develop a technique to deploy the PTV2 using a modified platform extraction. The Smart Release algorithm has been developed to track the extracted vehicle orientation until a desired separation condition is met. This paper outlined the testing that was performed on this system. The testing was designed to build confidence in the technique before employing it on a PTV2 test. The development of the Smart Release system and the Generation II avionics system included significant challenges. CPAS engineers met these challenges and ultimately delivered a system that is able to initiate the separation of the PTV2 and CPSS when a desired orientation is met. Additional tests scheduled before the PTV2 series provide an opportunity to gain further confidence in the system.

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The author would like to acknowledge the contribution of the entire CPAS analysis, avionics, and operations teams in developing and testing the algorithm described in this paper. The Smart Release technology was only a part of the Generation II CPAS avionics development project. As with any major integrated hardware and software development exercise, this project encountered set-backs and had to work within schedule constraints. The team met these challenges in a professional manner with a focus on the collection of high quality data.

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