

Orion MPCV Touchdown Detection Threshold Development and Testing

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A robust method of detecting Orion Multi-Purpose Crew Vehicle (MPCV) splashdown is necessary to ensure crew and hardware safety during descent and after touchdown. The proposed method uses a triple redundant system to inhibit Reaction Control System (RCS) thruster firings, detach parachute risers from the vehicle, and transition to the post-landing segment of the Flight Software (FSW). An in-depth trade study was completed to determine optimal characteristics of the touchdown detection method resulting in an algorithm monitoring filtered, lever-arm corrected, 200 Hz Inertial Measurement Unit (IMU) vehicle acceleration magnitude data against a tunable threshold using persistence counter logic. Following the design of the algorithm, high fidelity environment and vehicle simulations, coupled with the actual vehicle FSW, were used to tune the acceleration threshold and persistence counter value to result in adequate performance in detecting touchdown and sufficient safety margin against early detection while descending under parachutes. An analytical approach including Kriging and adaptive sampling allowed for a sufficient number of finite element analysis (FEA) impact simulations to be completed using minimal computation time. The combination of a persistence counter of 10 and an acceleration threshold of approximately 57.3 ft/s² resulted in an impact performance factor of safety (FOS) of 1.0 and a safety FOS of approximately 2.6 for touchdown declaration. An RCS termination acceleration threshold of approximately 53.1 ft/s² with a persistence counter of 10 resulted in an increased impact performance FOS of 1.2 at the expense of a lowered under-parachutes safety factor of 2.2. The resulting tuned algorithm was then tested on data from eight Capsule Parachute Assembly System (CPAS) flight tests, showing an experimental minimum safety FOS of 6.1. The formulated touchdown detection algorithm will be flown on the Orion MPCV FSW during the Exploration Flight Test 1 (EFT-1) mission in the second half of 2014.

Nomenclature

σ = Standard deviation from the mean

I. Introduction

THE first test flight of the Orion Multi-Purpose Crew Vehicle (MPCV) is set for September of 2014. This mission is titled *Exploration Flight Test-1* (EFT-1) to underscore the fact that Orion will be NASA's primary vehicle for Human Exploration of Space. The EFT-1 mission consists of two orbits with the first one circular and relatively close to Earth, while the second orbit is highly elliptical and will bring Orion back at speeds high enough to nearly simulate lunar return or return from some other exploration destination. Orion entry will be guided to desired water landing off the coast of the Baja Peninsula. Two Drogue and three Main parachutes will be used to slow the vehicle to a gentle landing in the Pacific Ocean. At this point the vehicle must release the parachutes and shut down the Reaction Control System (RCS) jets. The RCS jets will be used until touchdown to properly orient the vehicle for impact with the water. The chutes need to be released as soon as possible after impact with the water to reduce the risk of the capsule flipping upside-down, while the RCS jets need to be safed to eliminate the possibility of firing the jets underwater. There is only limited testing available for firing jets in water, and there is potentially

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high risk to the vehicle if underwater firing does occur. Thus, the Orion design includes an automated touchdown detection system. For crewed missions, this system will assist (i.e. provide touchdown indication) and backup an incapacitated crew, although the system is prime for any unmanned missions.

During the first phase of design of the Orion touchdown detection system many concepts were explored, including navigated altitude, altitude rate, acceleration, and even salt-water detection. Methods used on other spacecraft and landing systems were also evaluated. In the end, a simple yet robust method was chosen: the magnitude of the acceleration output by the Orion Inertial Measurement Unit (OIMU). This method only relies on the OIMU hardware, which has dual redundancy for EFT-1 and is planned to have triple redundancy for future missions. No other navigated solution (i.e. position, velocity, or attitude) is required, and the logic is relatively simple, making the technique highly reliable and robust. All that is needed is to determine the proper thresholds (RCS termination and chute release) for touchdown declaration that will provide the desired detection reliability, while maintaining sufficient safety margin against any false detections. More details on the design choice and initial performance can be found in [1]. This paper will detail the design trade study that lead to the final implementation and the analysis conducted to design the thresholds and assess performance and safety margins.

II. Touchdown Detection Logic Overview

The crew aboard the MPCV is the prime mechanism for touchdown detection during a crewed mission. In the case that the crew is not present or unable to perform touchdown detection duties, an automated system will declare touchdown. The automatic system will be activated 60 seconds after the drogue jettison command and below 1500-foot altitude. If the altitude data from the Global Positioning System (GPS) and the three barometers is deemed faulty, the automatic system will be activated 60 seconds after the drogue jettison command with no restrictions on altitude. Crew input to the declaration of touchdown is discussed further in Section VII. Additionally, a backup timer will be used if altitude data is deemed healthy. This will serve to declare touchdown in the case that both the crew and algorithm fail to detect touchdown. Selection of the backup time length is detailed in Section IV.

III. Design Trade Study

A. Background

The touchdown detection algorithm concept consists of checking vehicle IMU data against a specified threshold, with the expectation that impact will generate an identifiable signature in the data. Five design decisions were included in a trade study to determine the optimal configuration of the algorithm. They include detection method, detection frequency, threshold value, persistence counter, and use of filtering. The variable threshold and persistence counter parameters allow for tuning of the algorithm to detect a range of signatures such as terrestrial (land) landings or water landings.

B. Analysis Tools

The parachute dynamics for the study were generated using up to 1109 Decelerator Systems Simulation (DSS) Monte Carlo runs for each of six parachute scenarios, described in Table 1. The impact dynamics were generated by 1811 LS-DYNA runs using initial conditions bounded by the final conditions from DSS.

Table 1. Parachute Scenarios Modeled with DSS to Generate Dynamic Data for Safety Analysis

DSS run descriptions
Nominal 3-mains
3 mains with one late chute inflation
2 mains (one chute failure) with one late chute inflation
2 mains (one chute failure)
3-mains with at 6σ wind dispersions
3-mains with at 6σ wind dispersion & increased vertical winds

The impact portion of touchdown detection analysis utilized MATLAB scripts, which processed data from the LS-DYNA simulation for impact dynamics. LS-DYNA is a finite element analysis simulation that is

computationally very expensive and time consuming to run. Therefore, a bounding set of 1811 test cases was established. MATLAB scripts, implementing IMU models and the detection algorithm, were then run on the resulting impact data with varying parameters for analysis. The results of the detection algorithm were then expanded from 1811 cases to approximately 53300 cases with a Kriging surface fit using additional MATLAB scripts. The Kriging process is discussed further in Section V.

The parachute dynamics portion of touchdown detection analysis utilized MATLAB scripts processing data generated by the Decelerator Systems Simulation (DSS) for parachute dynamics. DSS is a FORTRAN program wrapped in MATLAB that can be run in a Monte Carlo fashion. 1109 runs were made for each of the 6 parachute scenarios studied. The same MATLAB scripts implementing the FSW model used for the impact analysis then processed the DSS data with varying parameters. The analysis tools used to further refine the persistence counter and threshold parameters are discussed in Section IV and Section V.

C. Detection Frequency

Although the flight software operates at 40 Hz, data is available for touchdown detection at 200 Hz. The detection algorithm was run on sets of LS-DYNA data with varying threshold values. By increasing the threshold, the algorithm is pushed to the point at which it begins missing the softer landings, giving a basis for comparison. The results are shown in Figure 1.

It is seen that failed detection cases are present at a lower threshold with 40 Hz data than with 200 Hz data. This was true for both the accumulated delta-v and acceleration detection methods. In both methods, the number of failed detections is greater using 40 Hz data over 200 Hz data. Therefore, improved detection performance can be achieved by using 200 Hz data.

To continue the trade study, a test threshold must be established for consistency. It was chosen to set a threshold such that the no detect FOS equaled 1.0. This would give the greatest early false detect FOS, yet still catch the softest impact. The data from Figure 1 indicates that this threshold will be in the range of 20 – 25 ft/s² for the acceleration method, and a similar analysis shows 8.9 – 14.9 ft/s for accumulated delta-v method. The values chosen to proceed with the study were approximately 21.9 ft/s² and 11.2 ft/s for the acceleration and accumulated delta-v methods, respectively, with the expectation that these values would be refined once the algorithm characteristics were finalized. Additionally, the FSW allows for independent thresholds for cutting away the parachutes (touchdown detected) and for RCS termination. The purpose of this capability is discussed further in Section V.

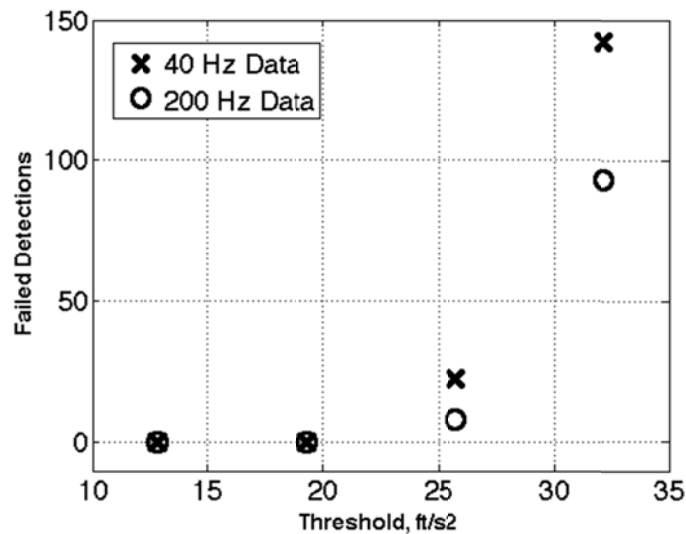


Figure 1. Failed detections as function of threshold for Algorithm Using 40 Hz and 200 Hz Data

D. Persistence Counter

The persistence counter is a concept used to increase safety margin and overall robustness by protecting against spurious events. A persistence counter of N requires that N consecutive data points exceed the threshold. By definition, earlier analyses done without a persistence counter are equivalent to a persistence counter of 1. This concept is visualized in Figure 2, the time history of measurements from a single run. For a detailed discussion of the persistence counter and factor of safety definitions, see [2].




Figure 2 shows that as the persistence counter increases, the effective maximum detection measurement decreases. This increases the early false detect FOS while decreasing the no detect FOS. Another approach to understanding the persistence counter is by realizing that the logic dismisses the (N-1) highest measurements in a sliding window N data points wide before triggering (if the Nth highest measurement is above the threshold).

Figure 3 shows that as persistence counter is increased, the impact FOS decreases using acceleration for detection, and the same approach can show that the FOS remains relatively unchanged using the accumulated delta-v measurements. Under parachutes, the FOS increases as the counter is increased when using acceleration measurements, as seen in the figure, and again remains relatively constant when using accumulated delta-v measurements. These results show that an increase in persistence counter will increase under-parachutes FOS at the expense of impact FOS. A persistence counter value of five was chosen to continue with the trade study, with the intention of refining the value once the algorithm characteristics were finalized.

E. Detection Method

Two detection methods were assessed in this trade study. The first method is based on the Δv accelerations as reported by the vehicle IMU. A lever arm correction is applied to the data to get values of the center of gravity (CG). This magnitude is then compared against a tuned threshold. If the threshold is tripped, touchdown is declared. The other method is based on accumulated change in velocity. A lever arm correction is also utilized in this case to output the velocity of the CG. The magnitude of the change in velocity over a given window of time is summed and compared against a threshold. If the threshold is tripped, touchdown is declared.

The shared pros of the two detection methods include the reliance solely on IMU data. Up to 1000 Hz IMUs on Orion MPCV provide fault tolerance, are rated to handle impact loads, are protected from space pressure vessel, and are the most reliable and fundamental piece of hardware on the vehicle. The navigation state of any kind is required to evaluate the IMU data and a simplistic design reduces weight. On the other hand, a detection method based on IMU data will require properly designed thresholds. The signature must be large enough to be distinguishable from other nominal and off nominal dynamic events.

Method	FOS
Δv	2.6
Acceleration	4.8
Altitude	2.0
Rate of Change	1.3
Pressure	3.2
Temperature	2.5

Table 2 compares the safety FOS of the detection methods when the impact performance FOS is driven to approximately one. The acceleration method provides for a larger safety margin under the parachutes for three of the six cases, including the three driving cases of 6σ winds, 6σ winds and vertical winds, and 2 main parachutes with a late inflation. The Δv method provides for a large safety margin for the other three cases.

Additionally, the acceleration magnitude method utilizes simpler logic and previous studies have shown that it demonstrated faster detection times. The acceleration magnitude method was chosen to continue the trade study.

F. Filtering

The impact of a 2nd order filter with cutoff frequency of 10 Hz and a damping ratio of 0.707 used on the rates and accelerations was studied. In order to perform the lever arm correction, the angular acceleration of the IMU is required. Since this is not available directly from sensors, it is backed out from the body rate data by dividing the difference between consecutive body rates by the IMU time step. This creates the possibility of artificial angular accelerations produced by noise in the body rate data. The analysis showed that filtering had little effect on the FOS, while providing protection against artificial acceleration spikes, therefore filtering is included in the algorithm. A flowchart of the final design of the touchdown detection is seen in Figure 4.

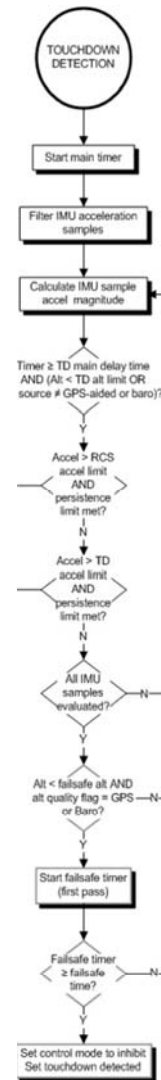


Figure 4. Touchdown Detection Flowchart