Post-Flight Quantification of LOFTID Aeroshell Deflection Using Feature Tracking

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Brief Author Biography: Hannah Alpert received her PhD in Aeronautics and Astronautics from Stanford University. She is currently working as an Aerospace Systems Engineer at NASA Ames Research Center in the Entry Systems and Vehicle Development Branch.

Introduction: The Low-Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID) was a flight demonstration of Hypersonic Inflatable Aerodynamic Decelerator (HIAD) technology, which has the potential to enable delivery of heavy payloads to Mars, Venus, and Titan, as well as return to Earth. Unlike rigid aeroshells that are constrained by the diameter of the launch vehicle shroud, inflatable aeroshells can be deployed to a much larger drag area, thus allowing a more massive spacecraft to begin its deceleration at higher altitudes and experience less heating [1], [2]. On November 10, 2022, the LOFTID reentry vehicle launched aboard a United Launch Alliance Atlas V rocket to low-Earth orbit. The aeroshell was inflated to its full 6-meter diameter, and the vehicle then successfully re-entered the atmosphere, landing in the Pacific Ocean.

The aeroshell was composed of seven tori bound together by high strength straps to create a 70-degree half-angle sphere-cone, and the forebody was covered with a flexible thermal protection system (FTPS) (Fig. 1). The centerbody of the vehicle housed six visual cameras. Each camera was made up of 1920 × 1080 pixels and had a field-of-view (FOV) of 85.4° × 55.6°, resulting in a resolution of less than 0.1” at all locations on the aftbody side of the aeroshell. The approximate locations of the cameras and their associated FOVs is shown in Fig. 2.

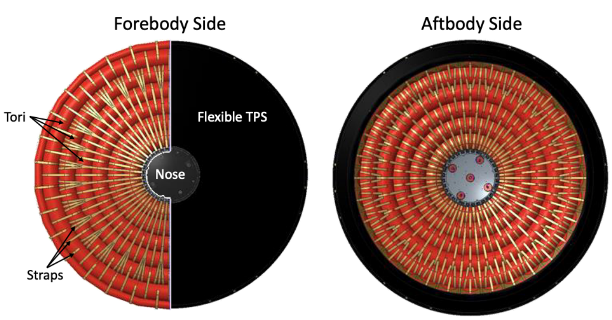

Figure 1. **Forebody and aftbody of the LOFTID aeroshell.**

The high loads experienced during flight resulted in the cone of the aeroshell deflecting. This behavior was seen during the static load testing of the aeroshell in May 2021, in which loads ranging from 1,000 to 20,000 lbf were applied, and deflections of up to ∼1.7° were observed. The LOFTID team was interested in estimating the deflection of the aeroshell during the its entry into Earth’s atmosphere. Before launch, 1”-diameter black circles were drawn on select structural straps for tracking with the visual cameras; the change in position of these features could then be used to calculate aeroshell deflection angle.

Feature Tracking: The features remained visible to the visual cameras throughout most of the flight. A computer vision algorithm was designed using the *OpenCV* package in Python that allows the user to select a feature and track its coordinates throughout a video. A Discriminative Correlation Filter with Channel and Spatial Reliability tracker (CSRT) [3] was chosen due to its better accuracy and robustness when compared with the other tracker types built into *OpenCV*. The algorithm’s output was the coordinates (in pixels) of the feature throughout the video.

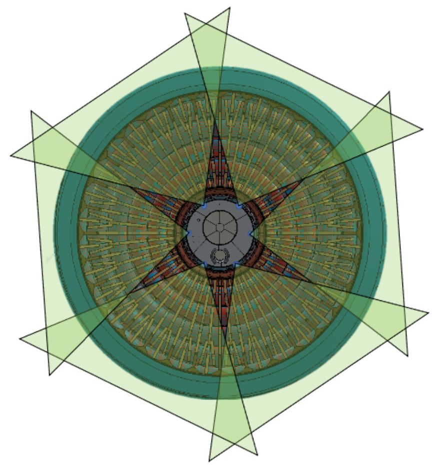

Figure 2. **Camera locations and associated aftbody side FOVs of the visual cameras.**

Deflection Angle Calculation: The aeroshell deflection angle calculation required the magnitude of the shift in pixels in y-direction (Δy_{px}) of the tracked feature and the distance of the feature from the camera location. A schematic describing the calculation is shown in Fig. 3. Assumptions included negligible movement in the x-direction, an initial half-angle of the aeroshell of 70°, and a constant linear distance between the nose of the cone and the feature (i.e., $H_1 = H_2$ in Fig. 3).

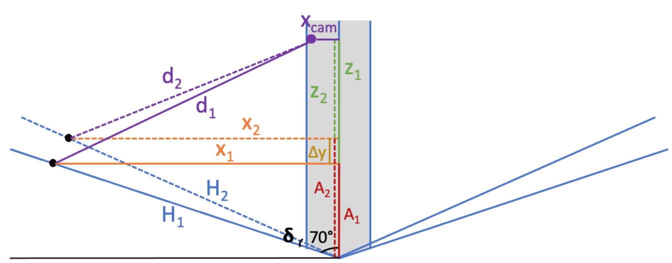

Figure 3. **Schematic of aeroshell deflection angle calculation.**

The distance (d_1) between the camera and the feature was calculated as:

$$d_1 = \sqrt{(x_1 - x_{cam})^2 + z_1^2} \tag{1}$$

where x_1 is the horizontal distance between the center of the cone and the feature, x_{cam} is the horizontal distance between the center of the cone and the camera, and z_1 is the vertical distance between the feature and the camera. The vertical shift (Δy) is calculated by multiplying Δy_{px} by the spatial resolution of the camera at distance d_1. The updated vertical distance between the nose and the feature (A_2) is calculated by adding Δy to the initial vertical distance (A_1). Finally, the deflection angle (δ) is calculated as:

$$\delta = 70^\circ - \cos^{-1}(\frac{A_2}{H_1}). \tag{2}$$

Validation: The deflection angle calculation method was validated using video from static load testing of the aeroshell. This test included loading the aeroshell with the following loads sequentially: 1000 lbf, 10,000 lbf, 20,000 lbf, 1,000 lbf. The aeroshell deflection was calculated from laser scans of the vehicle under each loading condition. For the radial on which the camera was positioned, the deflection angles ranged from 0.2° at 1,000 lbf up to 1.7° at 20,000 lbf; these measurements as well as those at the intermediate loads are shown in Table 1. Although the tracking features had not yet been drawn on the straps at the time of the static load testing, features were chosen that were at similar y-coordinates to the circles (Fig. 4). The computer vision algorithm computed deflection angles from the static load test video and found them to be very similar to those determined from the laser scans, as shown in Fig. 5 and listed in Table 1, validating the process described above.

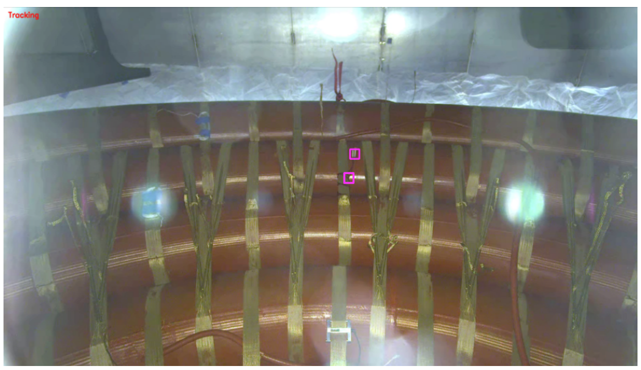

Figure 4. Frame from video taken during static load testing.

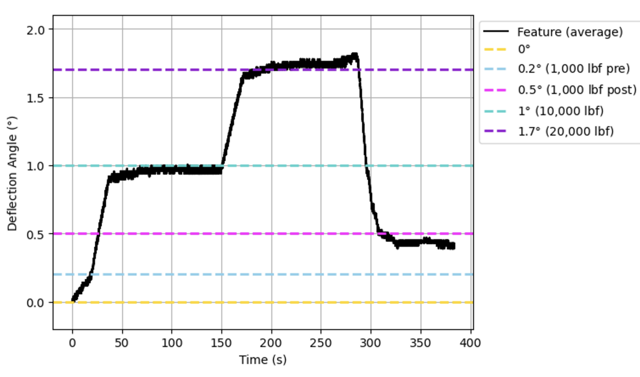

Figure 5. Deflection angle calculated from static load test video, with dashed lines denoting key deflection angles determined from laser scans.

Flight Video Analysis: For each of the six videos (one from each camera), the circle nearest to the center of the frame was tracked for a ten minute period that included peak pressure during atmospheric entry. An example of a video frame with a box tracking one of the circles is shown in Fig. 6. The circles were obscured in some of the frames due to plasma saturating the video, so those frames were omitted from the analysis.

Table 1. Static Load Test Data from Laser Scanning (LS) and Feature Tracking (FT)

Load	Deflection (LS)	Deflection (FT)
1,000 lbf	0.2°	N/A
10,000 lbf	1.0°	0.96°
20,000 lbf	1.7°	1.74°
1,000 lbf	0.5°	0.43°

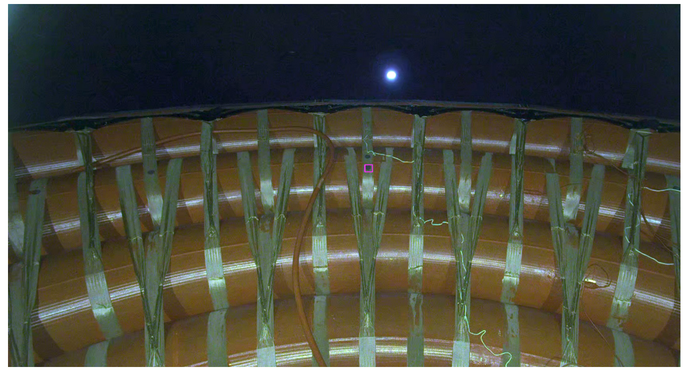

Figure 6. Frame from video taken during flight, with a box around the feature that is being tracked.

Deflection angles were calculated relative to the configuration of the aeroshell at the end of the video, as a significant jump in aeroshell configuration was observed shortly before the start of the pressure pulse, likely related to the innermost torus shifting into a mating groove in the vehicle centerbody once a non-negligeble pressure force had been applied. The angle of deflection between final aeroshell configuration and peak pressure was ~0.8-1° (Fig. 7). The configuration of the aeroshell at the end of the video likely corresponds to a deflection of 0.3-0.5°, as it was still under a load of ~1,000 lbf and had already experienced peak loading. Thus, the final deflection angle is likely to be in the range of ~1.3°. Based on static load testing results, this would correspond to a load of ~15,000 lbf at peak pressure.

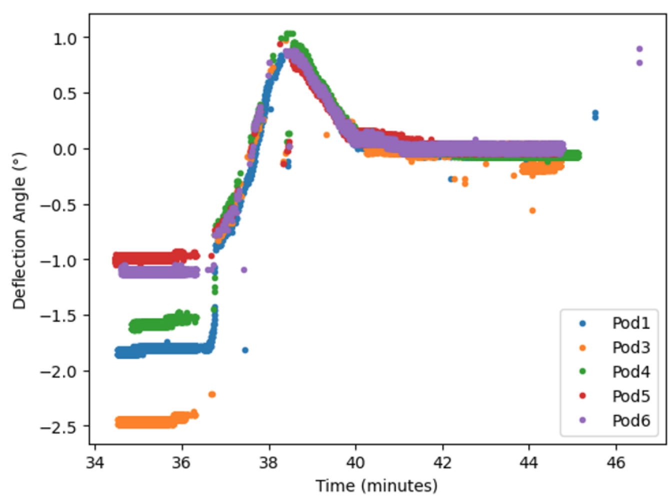

Figure 7. Aeroshell deflection compared to the final aeroshell configuration, based on feature tracking from each of the six cameras.

References:

[1] Cassell, A., et al. (2020) *White Paper for Planetary Sciences Decadal Survey, 2023-2032*.

[2] Dillman, R., et al. (2018) *IPPW*.

[3] Lukezic, A., et al. (2017) *CVPR*, 6309-6318.