

A Reliable and Cost-Efficient Data Acquisition System for MIL-HDBK-1763-Compliant Static Ejection Testing of Aircraft External Stores

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Before integrating a new external store onto a fighter aircraft, a ground static ejection test is required to evaluate separation safety, identify potential collision risks, and collect engineering data required by MIL-HDBK-1763 for aircraft–store compatibility assessment, including store displacement, attitude, velocity, and ejection force during release from the pylon. This research develops a data acquisition system for ground static separation tests and collects key separation parameters specified in MIL-HDBK-1763 including ejection force, store attitude and displacement during release from the pylon. The system consists of a calibrated high-speed camera system, a ground ejection module and an in-house image processing software. The software performs stereo camera calibration, store displacement, velocity, attitude and ejection force estimation throughout the separation process. Experiments using an external fuel tank model ejected from an aircraft pylon show that the system can accurately capture and estimate states at 400 frames per second. The displacement error is 1 mm at a 1σ confidence level. The high-speed camera system uses commercial off-the-shelf hardware, resulting in a very low total cost. The use of commercial off-the-shelf hardware significantly reduces implementation cost compared with traditional military photogrammetry systems. The developed solution provides a practical and reliable tool for MIL-HDBK-1763-compliant static ejection testing and aircraft-store compatibility assessment.

Keywords: Static ejection test, Ground test, High-speed data acquisition, Cost-efficient, MIL-HDBK-1763

I. Nomenclature

$\boldsymbol{R}$	=	Rotation matrix of store
$\boldsymbol{t}$	=	Translation vector of store
$\boldsymbol{P}$	=	Marker's position vector at initialization time
$\boldsymbol{Q}$	=	Marker's position vector at current time
$\boldsymbol{m_{store}}$	=	Mass of store [kg]
$\boldsymbol{a_{store}}$	=	Acceleration of store [m.s^{-2}]
$\boldsymbol{g}$	=	Acceleration due to gravity [m.s^{-2}]

II. Introduction

The store separation safety evaluation is a critical stage in the aircraft-store integration process, as unsafe separation can lead to collisions between the store and the aircraft [1]. To reduce these risks, military standards

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require ground testing assessment of store separation behavior before flight testing. Specifically, MIL-HDBK-1763/Test 110 describes a list of static ground separation tests to collect engineering data for separation safety evaluation of separation and dynamic compatibility between the aircraft and the store, including displacement, attitude, velocity, and ejection force [2].

High-speed military camera systems have been developed worldwide that can estimate full six degrees of freedom (6-DoF) data with high accuracy. However, these systems require high investment costs and complex calibration procedures [3]. A more common approach is to use inertial measurement units (IMU) combined with GPS positioning data, and a data fusion algorithm is used to calculate the 6-degree-of-freedom state. However, these often accumulate drift and are inefficient in store conditions under the aircraft wing or static ground tests [4]. In recent years, inexpensive computer vision systems integrated on embedded computing platforms have shown powerful capabilities in three-dimensional positioning.

In that context, this paper presents a low-cost and highly flexible high-speed 6-DoF trajectory acquisition system based on a stereo vision configuration combined with an embedded computing platform. The main contribution of this work is the development and experimental validation of a low-cost data acquisition system specifically designed for MIL-HDBK-1763 static ejection testing. Unlike conventional photogrammetry systems that require specialized hardware and complex setup procedures, the proposed system combines commercial off-the-shelf high-speed cameras, a flexible stereo calibration framework, and dedicated image processing software to provide automatic estimation of store displacement, attitude, velocity, and ejection force during static ejection testing. The system was experimentally validated using a representative external store model and demonstrated measurement accuracy suitable for aircraft-store compatibility assessment.

III. A Reliable and Cost-Efficient Data Acquisition System for MIL-HDBK-1763-Compliant Static Testing of Aircraft External Stores

A. System Overview

The system consists of a high-speed camera assembly, a ground ejection module and an in-house image processing software. The high-speed camera mounting structure allows flexible adjustment of the height, distance, and orientation angle between the two cameras and the store. The camera system has two high-speed cameras configured to operate at 400 frames per second with a resolution of 1280×720 pixels. The cameras are precisely aligned in position and orientation to ensure full coverage of the store's motion trajectory during the separation process (Fig.1).

The ground ejection module consists of a drop test rig, a separation control unit, and a data acquisition computer. The drop test rig includes a mounting rack, a pylon compatible with the store and a store damping. The separation control unit coordinates the ejection trigger and the image acquisition trigger of the two high-speed cameras. The computer acquires and stores image data from the two high-speed cameras when the trigger signal is activated.

The in-house image processing software, integrates functions for computing the intrinsic and extrinsic parameters of the camera system, estimating the position, velocity, attitude angles, and ejection force of the forced release mechanism, and training a model for store and marker detection in images. The camera calibration process, which determines the intrinsic and extrinsic parameters of the stereo camera system, is performed by detecting feature points on a standard checkerboard pattern and applying the disparity-based stereo vision theory presented in the work of Zhang [5]. The core algorithms of the in-house software are described in detail in the following section.

B. In-house image processing software

This study employs a calibrated stereo pinhole camera model to estimate the store states through three main steps. First, a machine learning model combined with image processing algorithms is used to detect the positions of markers in images acquired from the two cameras. The markers are assigned unique IDs in advance and are identified

using a marker tracking algorithm during the drop process. The tracking algorithm predicts marker positions based on data from previous frames and then matches them with the detected markers in the current frame. Next, a triangulation algorithm combines the detection results with the calibration parameters of the pinhole camera model to compute the three-dimensional positions of the markers in space. Finally, an absolute orientation algorithm compares the current marker positions with their initial positions to determine the state parameters, including position, attitude angles, velocity, and ejection force acting on the store generated by the ejector mechanism.

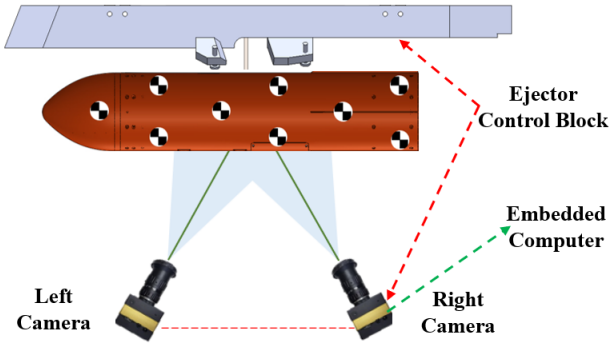


Figure 1. High-speed camera system

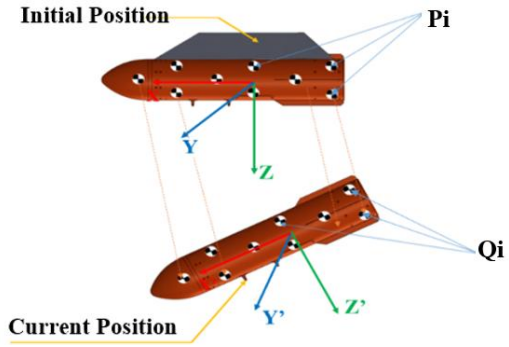


Figure 2. State estimation based on markers

Step 1: Position estimation by triangulation

After collecting the image coordinates of the object in the coordinate systems of the two cameras, the object position in the world coordinate system is estimated using the intrinsic and extrinsic parameters of the stereo camera system, combined with disparity-based stereo vision theory [6].

Step 2: State estimation using the absolute orientation method

To determine the post-separation attitude angles of the airborne store, the system detects geometric markers affixed to the store's surface (Fig.2). If at least four pairs of corresponding 2D–3D points are identified, the Perspective-n-Point method can be applied to estimate the pose transformation matrix, which includes the rotation matrix $\boldsymbol{R}$ and the translation vector $\boldsymbol{t}$ [7]. Assuming that a set of marker points at the initial position is obtained via triangulation as $\boldsymbol{P} = \{p1,...,pN\} \in \mathbb{R}3xN$ and the corresponding set of marker points at time T after separation $\boldsymbol{Q} = \{q1,...,qN\} \in \mathbb{R}3xN$, the goal is to compute the translation vector $\boldsymbol{t}$ and rotation matrix $\boldsymbol{R}$ relative to the initial position by formulating Eq.1. Equation(1) is solved by using Umeyama's absolute orientation algorithm [8]. the attitude angles Roll, Pitch, Yaw and the position can be computed using the method proposed by G. S. Labaugh and Queen Mary [9].

$$q_i = \boldsymbol{R} * p_i + \boldsymbol{t}, \quad with \quad i = 1...N \tag{1}$$

Step 3: Computation of the force exerted by the release mechanism on the store

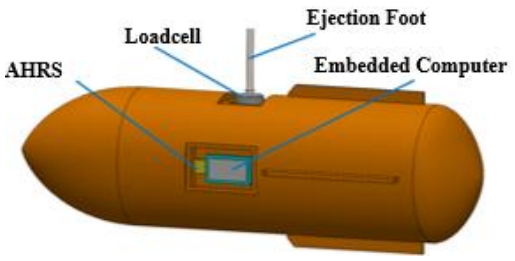


Figure 3. Method of verifying attitude, force

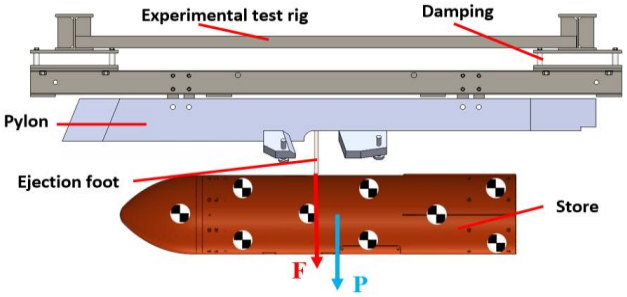


Figure 4. Forces exerted onto the store

The test system consists of a test rig, a damping pad, a pylon mounted on the rig, and the store. During the separation process, the release mechanism applies a force $\boldsymbol{F}$ on the store, which is also subjected to gravitational force $\boldsymbol{P}$ (Fig.4). Force exerted by the ejection foot (belongs to release mechanism) on the store is calculated by Eq.2:

$$F(t) = m_{bom} * a_{store}(t) - m_{store} * g = m_{bom} * \frac{d^2X}{dt^2} - m_{store} * g \tag{2}$$

IV. Verification of Proposed Data Acquisition System

A. Verification Setup

The aircraft external store model was designed to represent an external fuel tank, while ensuring consistency in mass, dimensions, center-of-gravity location, and moments of inertia. Tracking markers were attached to the model for trajectory tracking purposes. The store was equipped with a load cell, an AHRS unit, and an embedded computer to collect reference data (Fig. 3). These data were used to validate the accuracy of the ejection force and attitude estimated by the developed software .

The stereo camera system was configured with a baseline distance of 800 mm. The average distance between the camera system and the store during testing was approximately 2500 mm. Circular markers with a diameter of 80 mm were attached to the store surface to ensure reliable detection throughout the separation process. These parameters were selected to provide sufficient image resolution and measurement accuracy within the expected operating volume.

For velocity measurement, the velocity was estimated by taking the time derivative of the position data. In the ejection force accuracy evaluation, the results computed by the software were compared with the reference data from the load cell attached between the ejector mechanism and the store.

In the position measurement accuracy verification, the reference position were generated using a stepper motor system combined with linear guide rails. The stepper motors have an angular resolution better than 1°. At the same time, the linear guide rails provide linear translations along the three axes Ox, Oy, and Oz. The system have a control module that ensures time synchronization and coordinate frame alignment with the data and reference frames of the high-speed camera system (Fig.5). The displacement error is computed following the scheme shown in Fig.6. The camera resolution, exposure time, frame rate and ISO settings were configured to be identical to those used in the high-speed recording experiments.

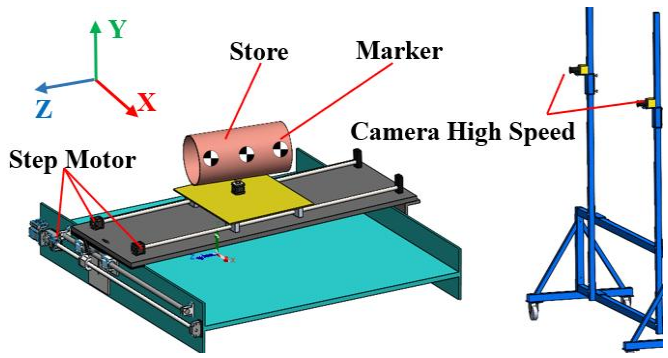


Figure 5. Method for position verification

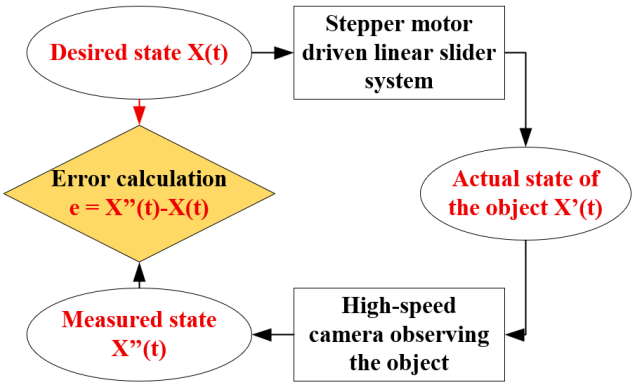


Figure 6. Diagram for position verification

B. Preliminary results

After conducting the store separation tests and the position measurements using the stepper motor–linear rail system, the comparison results of displacement are presented in Figs.7 and the velocity is presented in Fig.8, including both the reference values and the measurements obtained from the camera-based system. The displacement errors of the X and Y axes are both below 1 mm at 1σ. The achieved position accuracy demonstrates that the proposed system is suitable for static ejection testing applications. The measurement error is significantly smaller than the typical displacement observed during the initial release phase of the store. Therefore, the developed system can provide reliable trajectory data for aircraft–store compatibility assessment and separation safety evaluation. During all test runs, the marker tracking algorithm maintained stable detection performance without noticeable loss of tracking, ensuring continuous state estimation throughout the complete separation sequence.

The measured ejection force acting on the store is shown in Fig.9. The red curve represents the measured ejection force, the blue curve represents the resultant of the external forces acting on the store, and the dark blue curve corresponds to the gravitational component.

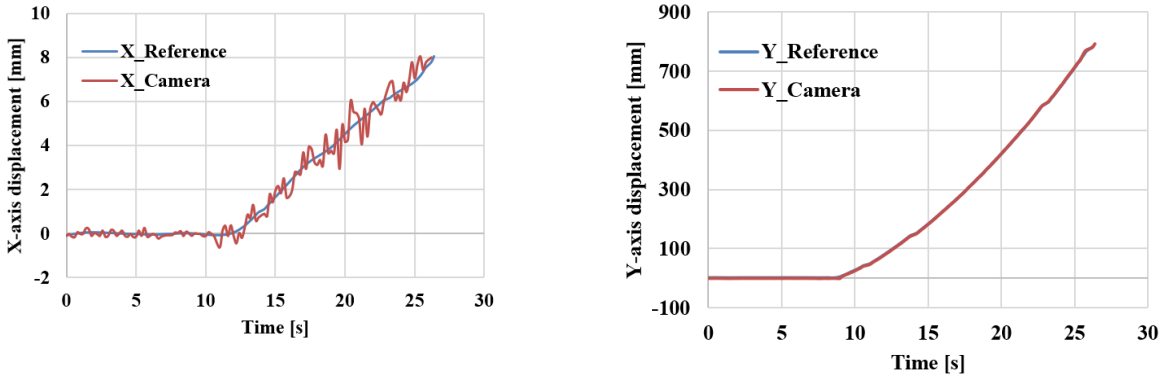


Figure 7. Displacement along the X and Y axes measured by the camera system and the encoder of step motor

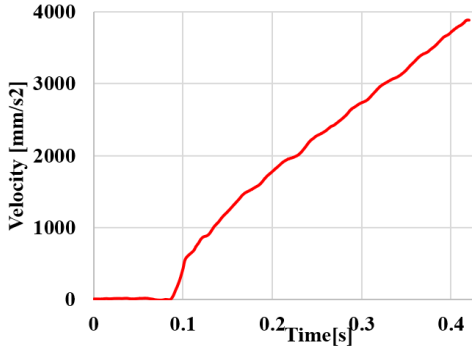


Figure 8. Velocity measurement

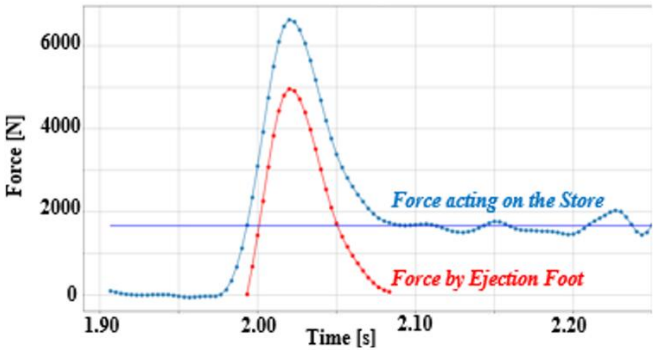


Figure 9. Ejection force measurement

The comparison between the estimated ejection force and the reference measurement confirms the validity of the proposed force reconstruction approach. The estimated force profile follows the same trend as the reference data during the complete release process. This result indicates that the proposed vision-based system can be used not only for trajectory reconstruction but also for evaluating the dynamic behavior of the release mechanism during static ejection testing.

The results show in Fig.10 that the measurement error remain within ±1° (1σ) for pitch, within ±1.5° (1σ) for roll and within ±1.5° (1σ) for yaw. These results demonstrate a high level of agreement with the reference measurements and confirm the effectiveness of the proposed stereo vision–based pose estimation framework for static separation testing.

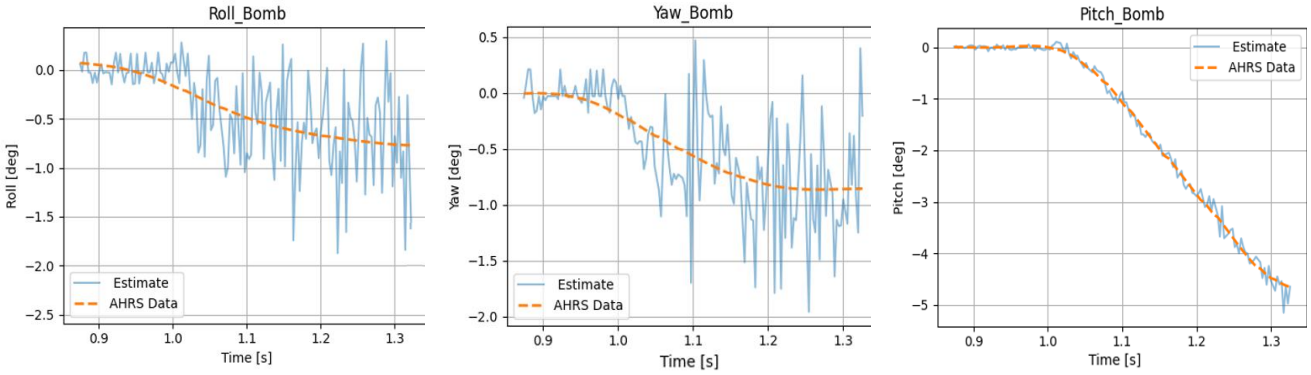


Figure 7. Attitude Angle Data from the Estimation Algorithm and AHRS Module

V. Conclusion

Compared with conventional aerospace photogrammetry systems, the proposed solution offers a simpler deployment process and significantly lower hardware cost. The use of commercial off-the-shelf cameras and a software-based processing framework reduces system complexity while maintaining sufficient measurement accuracy for engineering evaluation. This characteristic makes the system suitable for research laboratories and flight-test organizations with limited testing budgets.

Research on the Reliable and Cost-Efficient Data Acquisition System for MIL-HDBK-1763-Compliant Static Ejection Testing of Aircraft External Stores demonstrates that the system achieves a position measurement accuracy of 1 mm at a 1σ confidence level, while operating stably and reliably at 400 frames per second. This level of accuracy and reliability is sufficient for performing ground static ejection tests, allowing for a cost-effective safety evaluation before proceeding with flight tests of external store separation. Further tests evaluating the accuracy of the attitude measurement will be conducted in the near future. Additionally, the validated measurement results can be used as high-quality input data for store separation CFD simulations, contributing to improved accuracy in predicting and assessing the safety of separation under various aerodynamic conditions before flight testing.

The in-house image data processing software has demonstrated high performance and good accuracy, with the ability to process and collect data in real-time while maintaining low implementation cost. Furthermore, the system's flexible hardware architecture allows for easy adaptation to different test scenarios and varying measurement accuracy requirements, providing potential applications in flight separation tests.

The proposed system provides an affordable alternative to conventional aerospace photogrammetry equipment while maintaining sufficient accuracy for engineering evaluation of aircraft-store separation. The developed architecture can be extended to larger stores, different release mechanisms, and future flight-test instrumentation applications with minimal hardware modification.

The current validation focused primarily on position and force measurements during ground static ejection testing. Future work will include a more detailed evaluation of attitude estimation accuracy and an investigation of system performance under different lighting conditions and larger measurement volumes. The proposed architecture can also be extended to other aerospace testing applications requiring accurate motion tracking using low-cost hardware.

References

[1] S. R. Perillo and D. J. Atkins, “Challenges and emerging trends in store separation engineering: an Air Force SEEK EAGLE Office perspective,” in 47th AIAA Aerospace Sciences Meeting including The New Horizons Forum and Aerospace Exposition, Orlando, Florida, 2009.

[2] J. W. Williams, R. F. Stancil, and A. E. Forsman, “Photogrammetrics: methods and applications for aviation test and evaluation,” in 33th Annual International Symposium, SFTE.

[3] Nathan Murray, Bernard Jansen, Lichuan Gui, John Seiner and Roger Birkbeck “Measurements of Store Separation Dynamics”, 47th AIAA Aerospace Sciences Meeting including The New Horizons Forum and Aerospace Exposition.

[4] R J.Arnold and C.S.Eastein “AGARD Flight Test Techniques Series Volume 5 on Store Separation Flight Testing”.

[5] Z. Zhang, "A flexible new technique for camera calibration," IEEE Transactions on Pattern Analysis and Machine Intelligence, 2000.

[6] Faugeras, O., Three-Dimensional Computer Vision: A Geometric Viewpoint, MIT Press, Cambridge, MA, 1993.

[7] Horn, B. K. P., “Closed-form Solution of Absolute Orientation Using Unit Quaternions,” Journal of the Optical Society of America A, Vol. 4, No. 4, 1987, pp. 629–642. doi:10. 1364/JOSAA.4.000629.

[8] S. Umeyama, "Least-squares estimation of transformation parameters between two point patterns," IEEE Transactions on Pattern Analysis and Machine Intelligence (PAMI), Vol. 13, No. 4, pp. 376–380, April 1991.
[9] “Computing Euler angles from a rotation matrix” (G. S. Labaugh, Queen Mary, University of London).

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