DEVELOPMENT AND VALIDATION OF AN APPLICATION FOR PITCH DROP

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ABSTRACT

Of all the stages of the process of store separation, the flight test stage is the most expensive stage. Thus, the smaller the number of flights, the better. One step prior to in-flight tests is the pitch drop. In this stage, the use of a computer vision solution can assist engineers during the test to determine whether the test point was safe or not. When using cameras in any activity that requires accuracy in the results, it is necessary to perform the calibration of the optical system used in the tests. The IPEV has developed a solution that (1) the construction of a calibration field so that camera calibrations can be performed using a single frame; (2) a method for carrying out pitch drop test; (3) and an application that uses computational vision to process data from high-acquisition-rate cameras and generate the results in 6DoF. The development and validation of the solution are described in this work.

Keywords: image processing; store separation; real time; 3D analysis; camera calibration.

INTRODUCTION

In military aircrafts, the ability to release, when necessary, external stores during flight, such as weapons and auxiliary fuel tanks is very important [1].

During World War I, a bomber could simply release a store safely. This technique has become obsolete with the development of the closed cockpit. An arsenal of different launch mechanisms replaced the pilot's hand, and the small simple store was succeeded by an incredible variety of stores. From the moment the stores were ejected and not just released from a compartment under the aircraft, a great challenge arose because of the interaction between the aerodynamic environment and the dynamic characteristics of the external stores, the released store can collide with the aircraft, threatening the regular performance of the aircraft and the safety of the pilot.

In this scenario, the flight tests are made to provide the actual characteristics of the separation of the store that the analytical and soil methods try to predict [1]. However, while flight test data may be indisputable, its proper interpretation is another matter. The first problem is to be sure that the separation will be safe before the test is performed. The next step is to acquire the store trajectory data. The best information is obtained from high-speed cameras on board the aircraft. Ground-based cameras or videos of nearby aircraft may also be useful. Converting videos on a trajectory is a task of significant size from the point of view of quality and quantity. The most difficult part of the flight test procedure, however, is to maintain and measure the aircraft's flight conditions. New techniques are constantly being developed, but the implementation is slow due to the cost and dangerous nature of this type of test.

Of all the stages of the process of separation of stores, the flight test stage is the most expensive stage. Thus, the smaller the number of flights, better. The cost of testing, especially flight test, has been very strictly defined as the budgets of test programs have been decreasing [2]. Testing teams have been struggling to be as efficient as possible, looking for ways to get the most data in the shortest time possible. One challenge is to process and analyze data from a flight test before the subsequent flight can be scheduled and executed, as this process can take hours and / or days. This is especially true for store separation tests carried out to determine the maximum limits for the use of operational stores where the results of a test must be absolutely understood before moving to the next test point. Failure to do so may result in contact of the store with the aircraft and cause severe aircraft damage or loss of the test aircraft. Modeling and simulation have been used extensively to predict pre-flight store separation characteristics to achieve some efficiency in planning the test point. Rapid comparison of actual results with predictions is one way to further increase the efficiency of the assay. In addition to modeling and simulation, one of the steps that takes place before the flight tests are pitch drop test. These tests are fundamental because they allow the static evaluation of the separation in order to meet a minimum degree of safety.

The two main methods used to collect quantitative data from store separation tests are photogrammetry and telemetry with six degrees of freedom (6DoF TM) [2]. Each has advantages and disadvantages that can be understood in [2, 3, 4]. For this work, the photogrammetry technique was chosen for the development of a new computational solution to be used in load separation tests. This technique was chosen because of the high cost of inertial sensors (via telemetry) and the research institute already owns high-speed cameras.

Photogrammetry has added value for the experimental trials through the use of high-speed cameras (i.e. greater than 200 fps) and the use of computer vision. The use of a 3D computer-vision solution can assist engineers during the flight test to determine whether or not the test point was safe. In order to reconstruct the separation trajectory, one of the methods is through triangulation. This requires two or more cameras to be synchronized. When using cameras in any activity that requires accuracy in the results, it is necessary to perform the calibration of the optical system used in the tests.

In Brazil, the Flight Research and Testing Institute (IPEV) has carried out store separation tests for years, and the determination of the store separation trajectory was performed with a commercial tool (i.e. TrackEye). In addition, the process required many hours of work for the analysis of results and execution of flights test.

In order to eliminate the use of the commercial tool and to have technical mastery over all stages of the store separation test, IPEV, ITA, IAE, INPE and IEAv developed a solution that contemplates (1) the construction of a calibration field for calibrations of cameras can be performed using a single frame; (2) a method for carrying out pitch drop tests; (3) and software that uses computer vision to process data from high-acquisition-rate cameras and generate the results in 6DoF. The development and validation of the solution are described in this work.

STORE SEPARATION

The safe separation of a store from an aircraft is one of the main aerodynamic problems in the design and integration of a new store into an aircraft [5]. When a new store (i.e. bomb, missile or fuel tank, etc.) is developed or an existing store undergoes significant variations, it needs to be certified so that tactical aircraft can use them [6, 7]. Throughout the certification process, various tests are performed to ensure the safety of aircraft and store. One of the most important assessments in the certification process is to acquire a release envelope in which the store can be safely used. In order to obtain an operational launch envelope, it is possible to use some approaches, wind tunnel [8], computational fluid dynamics (CFD), pitch drop tests and flight tests [9]. These approaches are used to [10] obtain data in order to define the operational limit so that the release of stores can occur safely. This means that the store passes through the aerodynamic perturbation of the aircraft without affecting the aircraft or other stores released simultaneously.

Store separation analysis is one of the most challenging problems in aerospace engineering and is vital to ensure pilot safety, aircraft safety and mission success [11]. Basically, the analysis consists of studying the trajectory of a store when it is released from an aircraft. The various types of approaches play a critical role in the certification of stores because store separation data are collected so that the position and orientation of the store can be determined in order to establish the operational envelope of release.

To validate wind tunnel and CFD models, and to reduce the number of stores used in flight tests, by maximizing the engineering data collected during the tests, photogrammetry is used to measure the 6-degree trajectory of the store during and after the launch of the aircraft [10]. This 6DOF data is used to validate the separation models. Without photogrammetry, the store separation test is qualitative in nature and consists of several flights approaching the edge of the operational boundary small incremental steps.

In this sense, photogrammetric analysis is essential because it provides the position and orientation of a store relative to the aircraft during separation. Speeds and rates are also provided using smoothing techniques. To record store separation events, the cameras are mounted directly on the aircraft. Photogrammetric data collection must overcome a number of unique environmental factors and restrictive testing conditions, including vibrating cameras, strong sunlight or shadows, steam trails and obscure camera visions.

PHOTOGRAMMETRY

By far the most widely used technique for obtaining data in store separation tests is photogrammetry [9]. Although the detailed description of the use of the photogrammetric technique of each nation, or each company, varies, the basic method remains the same.

At NAVAIR (Naval Air Systems Command), for example, this technique has been used for more than 40 years [10]. At IPEV, we have been using this technique for decades, but only in the last five years have we invested resources and efforts to build a proprietary computing solution. Photogrammetric analysis in flight tests offers unique challenges, both from a technical and managerial point of view [10]. Photogrammetric analysis should take into account factors such as camera angle, camera movement, video quality, focal length, lens distortion, and environmental conditions. In addition, flight tests usually occurs in environments hostile to accurate measurements. From a personal point of view, the photogrammetric configuration involves a wide range of skills.

The quantitative data that are of interest to the team that analyzes the store separations are the time history of the position and orientation (x, y, z, Ψ, Θ, Φ) of the store relative to the aircraft [2]. This is often referred to as the 6DoF trajectory of the load. The first and second time derivatives of each of the amounts are also often of interest. Short-range photogrammetry is a useful tool to accurately determine the translational and rotational kinematics of the stores under test to support decisions about the risk of the test. In order to perform the estimation successfully, image sequences are recorded from several sensors specifically oriented to reliably observe the location variations of the object. Fortunately, the three-dimensional structure, as well as the initial 6DoF location of the reference and target objects, are known.

In addition, the modeling of lens distortion effects for each camera is pre-computed as an independent process. Traditional approaches use 2D observations of the object image to deterministically calculate the object's 6DoF state.

To collect position time history and orientation with 6DoF using photogrammetry, at least two high-speed cameras mounted on the aircraft (Figure 1) should be used to capture images of the store as it leaves the vicinity of the aircraft.

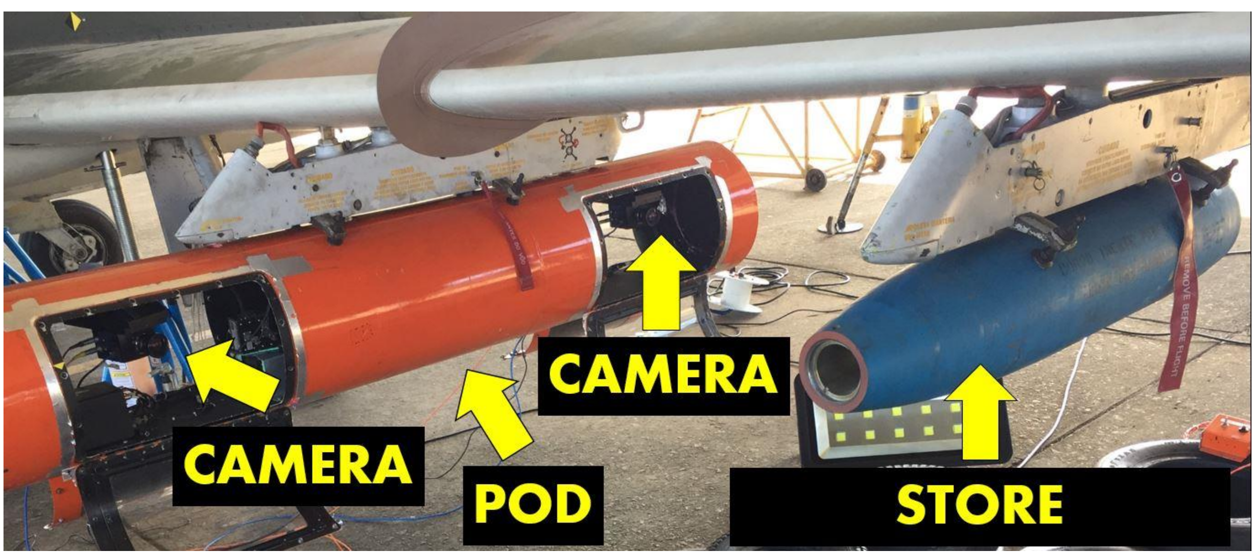


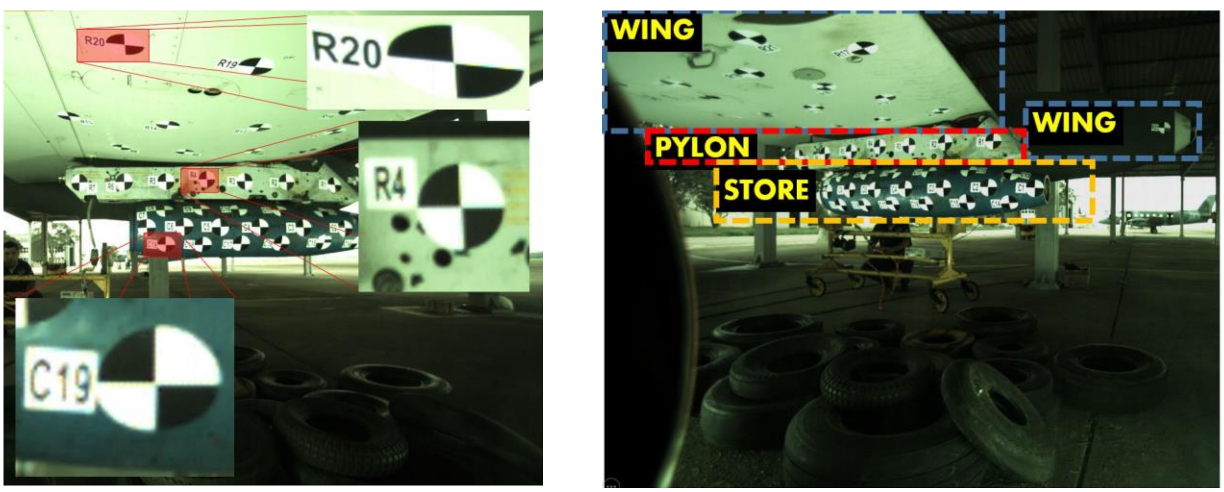
Figure 1 - POD used with two high-speed cameras.

DEVELOPMENT

The cameras used were Mikrotron Cube7 [12] configured at 400 frames per second, synchronized with each other using an internal camera mechanism. The rear camera was configured with region of interest (ROI) of 1184 x 1040 pixels and the front camera with 1248 x 968 pixels. The lenses used were Kowa 6mm C-Mount [13]. The aircraft used was an EMBRAER Xavante 4467. The store used at the test points was an inert store of approximately 130 kg.

Figure 2a shows the rear camera image with the ROI already configured. Also shown in detail is the type of marker used. It is possible to observe that each marker has an alphanumeric identification (e.g. C1, R1 - "C" is "Carga" (Store) in Portuguese, "R" is "Reference"). The identification of each target is important for the merge of the markers, used in 3D processing.

Figure 2b shows the front camera image with the ROI already configured. Also shown are the grouped markers on the Wing, Pilone, and Store. Groupings are important because the Asa and Pilone markers are in a rigid structure and will have very little variation of position during flight and store separation. These markers are used to determine the position of the store relative to the aircraft.



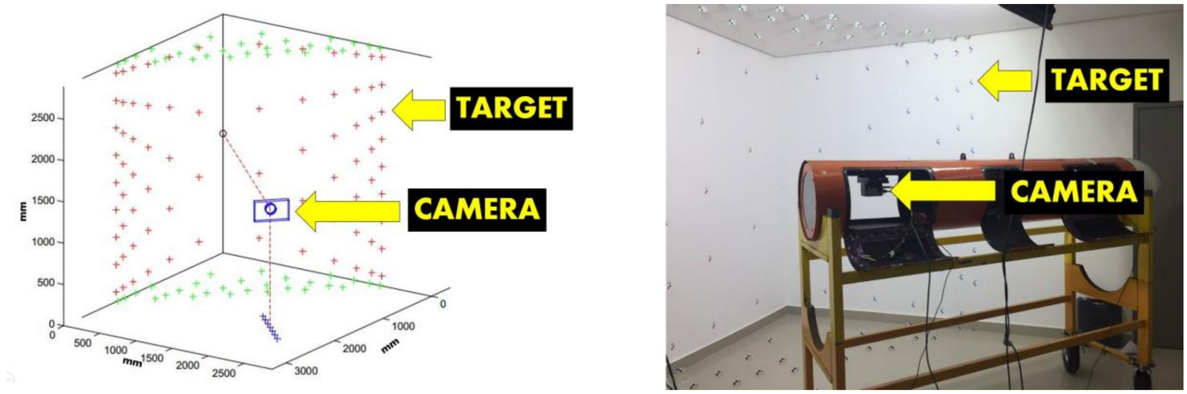
(a) **(b)**

Figure 2 – Image example of front camera and rear camera. (a) view of the region of interest of the rear camera with zoom in 3 targets (b) frontal camera showing the ROI and the overview of the targets.

The survey of the coordinates of each target was done using Tokyo Theodolite TM20C [14] and Nikon Total Station NPL-632 [15]. These equipment were also used to measure the horizontal and longitudinal leveling of the aircraft, performed before the start of the test points. For each store, the location of each target on the aircraft, pylon and store shall be measured against the defined coordinate system prior to the test point [2].

In addition, before the tests were carried out the calibration of the cameras was done using a geometric calibration field, built at IPEV. Calibration is required to determine the distortion characteristics of each camera. The detail of the calibration algorithm used can be seen in [16]. The positioning of the targets in the calibration field was previously determined and can be visualized in Figure 3a. In Figure 3b it is possible to observe the actual calibration scenario, considering the rear camera already positioned and configured in the photographic POD.

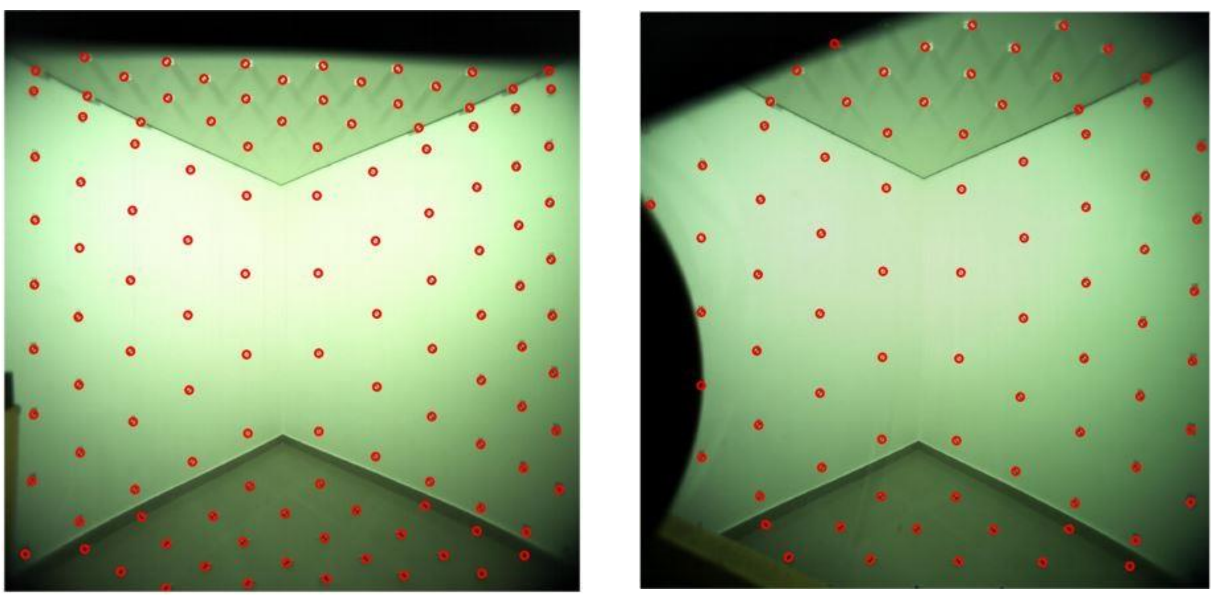
Calibration of cameras and other configuration information for each camera are stored for use in post-processing.



(a) **(b)**

Figure 3 – IPEV Geometric Calibration Field. (a) Position of each simulated target in order to be homogeneously distributed in the captured image (b) Example of calibration of the rear camera.

For each camera an image of the calibration field was obtained. After the calibration, the images were redesigned and can be visualized in Figure 4. It can be observed that in the cameras, the targets were homogeneously distributed, filling the entire frame.



(a) **(b)**

Figure 4 – Redesigned image of calibration field (a) rear camera (b) front camera.

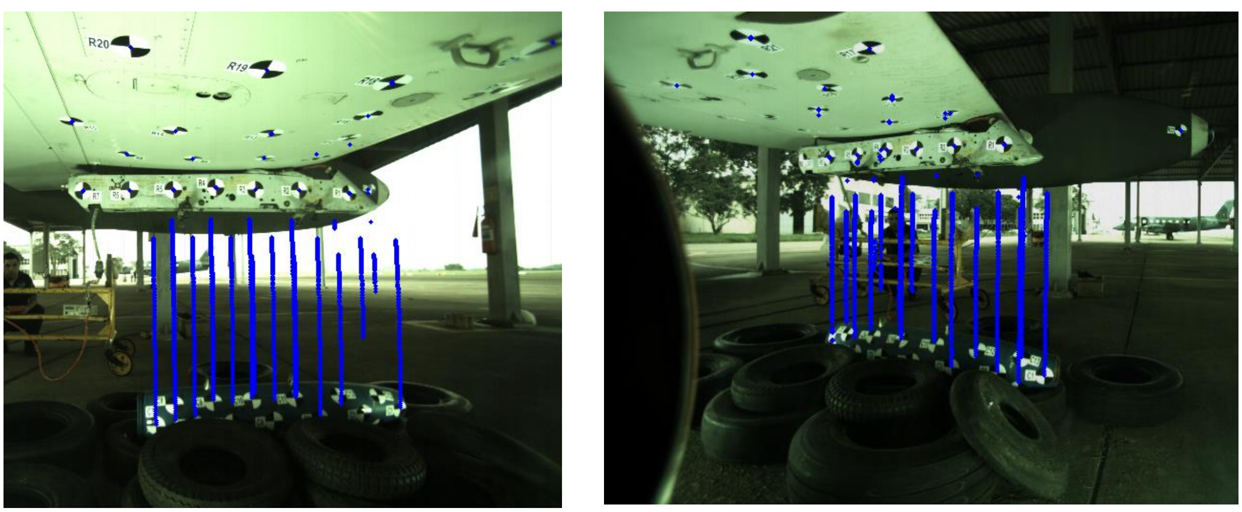
With the calibration field constructed, the mean square error was 0.748 pixel for the rear camera and 1.33 pixel for the front camera.

In [2], it says that a disadvantage of photogrammetry is the target selection step which really takes a lot of time. To minimize this problem, all targets are selected in both cameras in the same order. The selection is made semi-automatically. First, there is a manual selection of some point near the center of the target. Second, the image is processed iteratively in order to find the center of each target at the subpixel level. The obtained data is stored for use in post-processing.

Another disadvantage pointed out by [2], which is the problem of matching, is also solved from the moment all targets are selected in the same order. The correspondence of the targets is fundamental for obtaining the 6DoF.

After the test point, the camera images are downloaded from the cameras and a time slice of about 0.5 to 1 second is defined. The targets on the aircraft and store are first identified and then automatically traced to each camera image. Using the calibration of the camera, the survey of the aircraft's target and the data tracked to the targets in the aircraft, the location of the 6DoF of each camera in each image is estimated in an iterative solver. First, camera calibration is applied to the crawled data so that the effect of the lens curvature on the measurements is removed. Then an initial estimate of the camera's 6DoF location is used along with the camera's focal length to provide a prediction of where each of the measured targets should appear in the image (given the initial location estimate of 6DoF). The quality of the 6DoF location estimate is calculated by finding the residual distance between the predicted locations and measurements of each target; the smaller the waste, the better the estimate. A new 6DoF location estimate is calculated repeatedly, the destination locations in the image are predicted and the residuals are calculated until a minimum is reached.

In Figure 5 it is possible to observe the last frame of a test point considering the two cameras. The blue dots highlight the tracking of the targets during the test point. It can be seen that most targets were automatically traced during the test point. This is significant because it reduces post-processing time and increases the accuracy of information.



(a) **(b)**

Figure 5 – Target tracking during test point (a) rear camera (b) front camera

The pitch drop tests were performed at the IPEV facilities in São José dos Campos, SP, Brazil, and are fundamental for the development of the processing software. The validation of the software was done by comparing the information obtained, frame by frame, manually; and then using the old method (i.e. commercial software use). For each coordinate of the target (x, y), the error was measured in each video frame, considering the two cameras. Considering the errors of all targets, for the front camera, the mean square error obtained at x is 0.38 pixels and 0.83

pixels at y. For the rear camera, the mean square error obtained at x is 0.1 pixels and 0.78 pixels at y. The maximum error in the front camera was 3.5 pixels in x and 3 pixels in y; for the rear camera, the maximum error was 0.4 pixels in x and 3.9 pixels in y. This means that the maximum error is 8 mm, and the result is considered satisfactory.

CONCLUSIONS

This work had the following objectives:

(1) to approach the construction of a calibration field so that camera calibrations could be performed using a single frame. The construction of the calibration field was laborious (man-hour effort), however, great advantages were obtained such as obtaining the results of distortions from a single image and a small mean square error;

(2) also show a method for carrying out pitch drop tests. The accomplishment of this type of test involves great technical and managerial challenges, since the amount of people and equipment involved is numerous. The main steps to carry out this type of test were discussed; and

(3) finally, software that uses computer vision to process data from high-spped cameras and generate the results in 6DoF. The mastery over the entire flight test campaign process along with this software are key points for something we aspire to is the near real-time analysis of load separation trials using photogrammetry.

As future work, we suggest:

- the performance of new tests varying the position and attitude of the store during the fall;
- performing tests with higher light exposure; and
- adaptation of the software and alteration of the equipment for the realization of pitch drop tests, in order to obtain the results in near real time.

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