DESIGNING A VISION-BASED SYSTEM TO MEASURE IN-FLIGHT WING DEFORMATION

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Abstract

Flight performance drives the process of aircraft design. In this context, flexible structures are potential candidates to design aerodynamically efficient wings. However, aeroelastic effects inherent to very flexible wings are barely characterized in flight. The present project aims to propose a vision-based system to measure in-flight flexible wing deformation. The proposed vision-based system will acquire data through a pair of cameras installed over the wing of X-HALE, a highly flexible aircraft. Red markers on the wing will serve as reference points to infer wing deformation. Two computer vision strategies were selected to compose the proposed vision-based system: the red object detection procedure and the stereo vision procedure. The red object detection procedure is intended to obtain the two-dimensional coordinates of the red markers in the frames captured by each camera present in the pair of cameras. Using these image coordinates, the stereo-vision method is proposed to obtain the three-dimensional coordinates of the red markers. The initial step taken so far evaluates and tests both computer vision strategies. The stereo vision method and the red object detection procedure achieved their goals of identifying the desired physical and image coordinates respectively. Future work will be needed to implement both computational procedures sequentially and to assess the viability of applying the proposed vision-based system in a real-time application.

1 Introduction

Light-weight and high aspect ratio structures are potential candidates to design aerodynamically efficient wings. Consequently, aircrafts are becoming more flexible which intensifies the aeroelastic effects.

However, aeroelastic effects inherent to very flexible wings are barely characterized in flight.

The present project aims to propose a vision-based system to measure in-flight flexible wing deformation of a highly flexible aircraft named X-HALE. This vehicle was developed at the University of Michigan to gather aeroelastic flight data. The Aeronautics Institute of Technology in Sao Paulo has rebuilt X-HALE and has been operating the aircraft since July 2017.

X-HALE was designed to present an intense coupling between the structural and flight dynamics along with large and nonlinear wing deformation during flight.[1] Figure 1 exhibits X-HALE and its large in-flight wing deformation.

Fig. 1. X-HALE during regular operation.[2]

X-HALE is light-weight and its wing presents an extremely high aspect-ratio. The low structural weight and the induced drag reduction associated with these features are desirable in terms of aerodynamic performance. On the other hand, as illustrated by Figure 1, X-HALE presents intense in-flight wing deformation. This prominent phenomenon requires special attention and analysis.

To measure in-flight wing deformation, instrumentation techniques based on Strain Gauge and Computer Vision were compared. As a result, the Computer Vision-based technique was selected to be employed on the present project since it presents better data quality, noise rejection, durability and it is non-intrusive. In addition, vision-based systems have already been employed in flying vehicles successfully.[3, 4]

The present project aims to propose a vision-based system to measure in-flight flexible wing deformation. The system is intended to collect aeroelastic flight data that will enhance the knowledge about the behavior of flexible wings, possibly allowing and expanding their use in aircrafts. The initial step taken so far evaluates and tests the two computer vision procedures that composes the proposed vision-based system.

Computer vision is the enterprise of automating and integrating a wide range of processes and representations used for vision perception.[5] Computer vision deals with the design of algorithms capable of extracting useful information from images and videos automatically through computational procedures. In this context, a red object detection algorithm and the stereo vision technique will be approached and applied on the present project.

Object detection algorithms are intended to obtain the two-dimensional coordinates of a specified object frame by frame. There are many different strategies that can be used to detect an object such as looking for a specific color, shape or feature presented by the target object. Selection and implementation of an object detection strategy is determined based on the features of the target and the environment.

The stereo vision method is applied to extract the three-dimensional coordinates of objects captured by a pair of cameras. Through the image coordinates of the target object and the relative position of the cameras present in the pair of camera, the stereo vision procedure can obtain the physical coordinate of the target objects.

2 Methodology

The proposed vision-based system will acquire data through a pair of cameras installed over the wing of X-HALE. Red markers on the wing will serve as reference points to infer wing deformation. An onboard computer will control when images are captured and will also be used to store them.

The three-dimensional (3D) coordinates of the red markers will be acquired through the stereo vision method which will be applied along with an object detection algorithm. This algorithm is used to obtain the two-dimensional (2D) coordinates of the red markers for each camera present in the set of cameras. The stereo vision method thus is applied using these two image coordinates obtained through the detection algorithm. Both computational procedures were implemented through the MATLAB platform. Figure 2 presents the vision-based system workflow diagram.

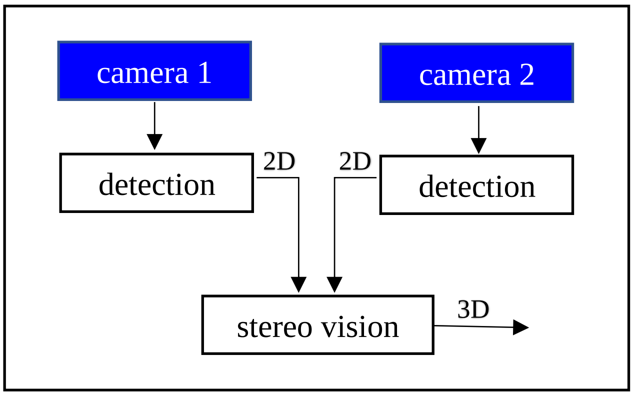

Fig. 2. System workflow diagram.

2.1 Red Object Detection Algorithm

To detect the markers, a color detection algorithm was applied. Through this algorithm, the image coordinates of red objects are identified. This algorithm will be used in images from both cameras present in the set of cameras to obtain the markers' 2D coordinates. The image coordinates obtained through the detection algorithm will serve as inputs for the stereo vision method, which will finally be used to obtain the desired physical coordinates.

Each colored frame is stored as a 3D matrix composed by three layers. As expected, the row and the column dimensions of the matrix represent the image's height and width. The third dimension composed by three layers represents the brightness values of the red, blue and green wavelengths present in each pixel. For example, red objects present high values in the red layer, and low values on the green and blue layers. This characteristic is explored by the red object detection algorithm presented in this section to identify red objects.

To detect red objects, the values that represents the image intensity of the color red are initially subtracted by its grayscale image. The grayscale image represents the intensity of light in each pixel. This subtraction operation is performed to differentiate bright pixels from red pixels. This differentiation is needed since as well as red pixels, bright ones are also represented by high numbers of intensity of the color red.

After subtracting the image intensity of the color red by the grayscale image, the result of this subtraction is converted in a binary image. In other words, pixels with numbers higher than a specified threshold will have a unitary value after the binary image operation has been executed. The specified threshold is defined to differentiate red objects from other objects with different colors.

Turning an image in binary allows the use of many different computational procedures capable of identifying connected components in the image. These connected components also called blobs, represent the objects which will be detected by the algorithm. After detecting the objects present in the frame, the coordinates of their centroid are calculated. These coordinates are considered the object image coordinates.

2.2 Stereo Vision Method

To perform the stereo vision method, the pair of cameras need to be calibrated. To calibrate the cameras, an App from MATLAB called Stereo Camera Calibrator was used. Intrinsic, extrinsic and lens distortion parameters were obtained through the mentioned App. The calibration process involved both cameras, in the desired stationary location, taking images of a black and white checkerboard positioned in many different orientations. These images are used by the camera calibrator to define the calibration parameters.

The intrinsic calibration parameters include the camera's focal length, optical center and skew coefficient. The extrinsic parameters represent the relative position and orientation from one camera to the other one. Lens distortion parameters are used to remove the image distortion present in the pictures caused by optical lenses. These three groups of parameters obtained though the Stereo Camera Calibrator App are used to perform the computer vision procedure.

During the calibration procedure, a parameter known as reprojection error is obtained and evaluated. The reprojection error is the distance, in pixels, between a specific point in a calibration image and the corresponding world point obtained through the stereo vision method and projected into the same image. [6] As smaller the reprojection errors are, more accurate the calibration parameters will be.

The stereo vision method that will be applied to obtain the markers' physical coordinates is called triangulation. Before applying this method, it is necessary to remove the distortion of the images caused by the lens. The lens parameters obtained during the calibration process are to remove the lens distortion.

Once the lens distortion is removed, the color detection algorithm presented in section 2.1 will be applied. With the calibration parameters obtained during the calibration process in addition to the coordinate images of the markers for both images, it is possible to apply the triangulation method using the undistorted images. Through the triangulation method, the markers physical coordinates will be obtained.

3 Results

Two different experiments were performed to first test the red object detection algorithm, and then, to test the stereo vision procedure. The first experiment was performed using an X-HALE flight video recorded using a digital camera.

During this experiment, red markers were placed on X-HALE's wings and the red object detection algorithm mentioned on this report was used to identify the 2D marker coordinates. The second experiment was performed to test the stereo vision procedure using two digital cameras to obtain 3D coordinates from two fixed targets.

3.1 Red Object Detection Experiment

The red object detection algorithm was applied to a X-HALE's flight video. A frame from this video is illustrated by Figure 3.

Fig. 3. Frame from a X-HALE's flight video.

Using the red object detection algorithm, it was possible to obtain the image coordinates of each red marker. The markers' image coordinates obtained through the red detection algorithm can be seen on Figure 4.

Fig. 4. Image coordinates acquired through the red object detection algorithm.

The image coordinates obtained through the red object detection algorithm are related to the markers' centroids. The coordinates represent the horizontal and vertical position of the markers' centroids in pixels. According to Figure 4, the vertical image distance between the closest and the farthest marker is about 450 pixels. This represents around 40% of the frame's vertical resolution; which is visually in accordance with Figure 3.

A prominent limiting factor for this detection algorithm is its inherent color dependency. During the flight, depending on the orientation of the camera to the sun, the markers have their colors changed. The occurrence of shadow over the markers also can change their color. The response of the color detection algorithm in situations that the markers have their color changed is extremely affected. This reveals a relevant constraint of any color detection algorithm.

3.2 Stereo Vision Experiment

Two red targets were placed in front of the camera's arrangement and the distances between the cameras and them were defined using the stereo vision procedure. To start the stereo vision procedure, the cameras were calibrated. Twelve pictures from a checkerboard in different positions were taken with both cameras present on the camera arrangement. These pictures can be seen on Figures 5 and 6.

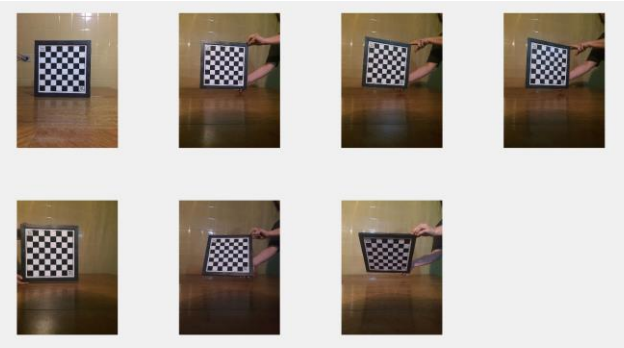

Fig. 5. Camera calibration pictures from camera 1.

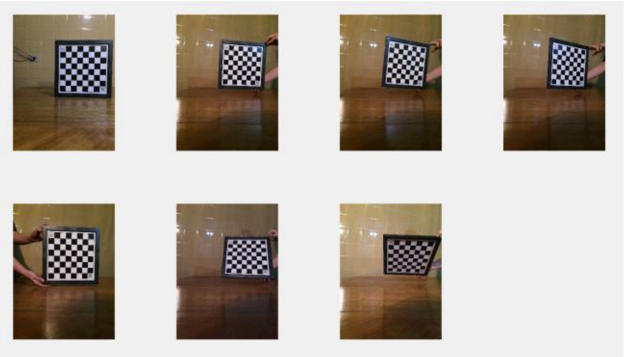

Fig. 6. Camera calibration pictures from camera 2.

Figure 7 illustrates the 3D model of the checkerboard obtained during the calibration process using the pictures present on Figures 5 and 6. Using MATLAB Stereo Camera Calibrator App, it was possible to define the physical coordinates of the checkerboard during the entire calibration procedure. Figure 7 also illustrates the axis directions and that the origin is determined by camera 1.

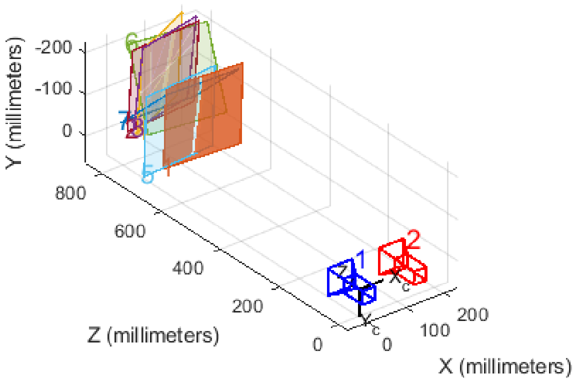

Fig. 7. Camera-centric view of the stereo calibration process.

The reprojection errors associated with the calibration pictures were obtained and presented by Figure 8. In general, reprojection errors higher than one pixel are not acceptable.[6] As presented by Figure 8, part of the calibration pictures presented reprojection errors higher than one pixel. This impacts negatively on the accuracy of the stereo vision method, but it does not disqualify the experiment.

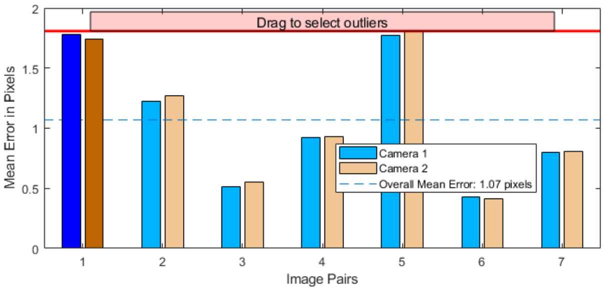

Fig. 8. Reprojection error by picture.

After calibrating the camera's arrangement, pictures of the two red targets were taken from both cameras. These pictures are presented by Figure 9.

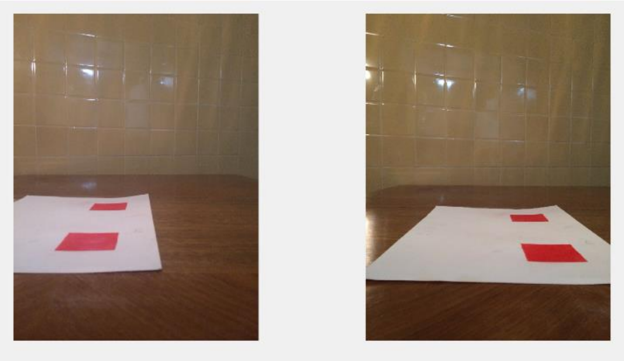

Fig. 9. View of the red targets from both cameras.

Using the camera lens parameter obtained through the calibration process, the distortion caused by the lens was removed from both pictures presented by Figure 9. Next, the image coordinates of the targets in frames from each camera were discovered using the red object detection algorithm.

The triangulation method was applied to get the target's distance from the cameras. Two red targets were placed in front of the cameras: one approximately 335 mm away and the other around 555 mm away. These distances were measured between the pair of cameras and the centroid of each red target. The physical coordinate of each target is presented on Table 1.

Table 1

	X (mm)	Y (mm)	Z (mm)
Target 1	-60.9865	89.4556	345.2212
Target 2	-58.1242	75.4603	560.0210

The distance between the set of cameras and the targets are represented by the Z coordinates in Table 1. The differences between the measured distance and the expected distance are lower than 10 mm. Taking into consideration experimental errors, the results obtained through the stereo vision procedure are satisfactory. Design errors with the camera placement led to a discrepancy in the distance of the red squares due to a slight tilt that was not overcome with additional security measures. Human errors in recording the precise distance of the targets are also a possible explanation in the deviation of the measurements.

4 Conclusion

Through the present project, it was possible to propose a vision-based system that could be applied to measure in-flight wing deformation. Using a set of two cameras and a color detection algorithm, it is possible to apply a stereo vision procedure to obtain physical coordinates.

The red object detection algorithm and the stereo vision procedure were tested and worked successfully on their goals; showing that these procedures could be applied to develop a vision-based system. The color dependency associated to the red object detection algorithm was evident during its experiment.

The next step will be to perform an experiment using the red object detection algorithm and the stereo vision procedure sequentially to obtain the desired physical coordinates. Once both algorithms are implemented sequentially, the viability of applying the algorithms in real time can be assessed.

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