Development of the flight laboratory for research of aerodynamic surfaces deformation

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Abstract. In-flight measurements are developing directions of aircraft testing. The practical implementation of these tests allows accelerating the development of new types of aircraft, the in-flight tests of serial samples, and their commissioning. Carrying out such tests is associated with high cost. In this paper the creation of a flight laboratory based on an unmanned vehicle is proposed. This will significantly reduce the cost of testing but in-flight conditions will be close to real tests. A system for recording experimental images during in-flight test was developed for conducting studies of deformations of aerodynamic surfaces. In this paper, the system based on single board computer is described; its main functions and features are considered. The results of laboratory tests of the developed system on a model of a deformable wing are presented.

1. Introduction

In-flight measurements as part of aircraft testing have developed recently. These measurements provide the ability to measure various parameters directly in flight [1]. The development of methods and techniques for conducting such tests is carried out by the international scientific and technical collaborations AIM and AIM2 [2]. Examples of practical tests include in-flight tests of the VUT100 Cobra [3], Airbus A320 [4] and even Airbus A380 [5]. The practical implementation of this approach allows to accelerate both the development of new types of aircraft, and the in-flight tests of serial samples, and their commissioning.

Carrying out such tests is associated with high cost. Therefore, the creation of a flight laboratory, based on an unmanned vehicle, is proposed in this work. On the one hand, this will significantly reduce the cost of testing, and on the other, the test conditions will be close to real in-flight tests: an increased level of vibration, the influence of aerodynamic loads and flight parameters on the deformation of the airframe, strong exposure to the Sun. The application of this approach will allow to improve existing and develop new methods and techniques for in-flight tests.

One of the little-known effects that arise during in-flight tests using optical methods is the decalibration of the cameras stereo pair [3]. Decalibration is the process of changing the extrinsic and intrinsic parameters of a system due to deformation of the fuselage and strong vibration. The extrinsic parameters of the stereo system define relative position of the camera and examined object, the intrinsic parameters include the focal length, the alignment of the lens and the matrix, etc. These parameters are used in various models, the essence of which is to describe the transformation of the
three-dimensional coordinates of a point in the world coordinate system into two-dimensional coordinates in image coordinate system (on the image plane). The relationship of the coordinates in most models are described using transformation matrix.

In-flight tests, in contrast to laboratory experiments, are accompanied by high levels of vibration, especially during intensive maneuvers of an aircraft. This leads to a change in the relative position of the cameras and the direction of their line of sight compared to these during calibration. Decalibration of the stereo system of the cameras, in turn leads to an increase in the measurement error. When designing the measuring system, all possible measures are taken to minimize the effect of the decalibration on the measurement results, but it is impossible to completely eliminate it. This is especially true for in-flight tests of a large aircraft, when the base of the stereo system can reach more than one meter.

In the in-flight experiment, the calibration matrices are pre-calculated on the ground. During the test due to deformation and vibrations of the airframe elements of the aircraft, the cameras move relative to each other, the objects move relative to the cameras, etc. This leads to a change in the actual values of the coefficients of the calibration matrices during the registration of the experimental images. The processing of such images with the help of matrices obtained on the ground before the flight leads to significant errors in the measurements.

Recalibration is the inverse procedure for obtaining the closest to the actual coefficients of the calibration matrices. In practice an optimizing algorithm is used for recalibration to minimize triangulation errors in order to obtain best possible matrix coefficients [3]. One of the purposes of this study is to refine the recalibration procedure during in-flight tests.

2. Software and hardware development for flight laboratory
Skywalker 1680 unmanned aerial vehicle with a wingspan of 1.7 m was used as the basis of the laboratory (figure 1). It is equipped with an FPV (First Person View) system and an autopilot system. To conduct studies of deformations of aerodynamic surfaces, a software and hardware system for recording experimental images on board of an unmanned aerial vehicle was developed. The main tasks of the system are to capture images from the cameras and transfer them to a personal computer through wireless interface. Recorded images should also be accompanied by data with flight parameters (altitude, speed, acceleration). All functions must be controlled remotely from personal computer by wireless channel. The system should have the following properties: low weight, small dimensions, high autonomy, the ability to interface two digital cameras at the same time, the ability to be remotely controlled and transmit data wirelessly. The developed system is based on a “Raspberry Pi CM 3” Lite single-board computer, a “StereoPi” expansion card [6], and two digital video cameras. The schematic diagram of the system is shown in figure 2.

![Figure 1. Installation of the developed system on board of the unmanned aerial vehicle (left), the single-board computer with a connected stereo cameras system (right).](image-url)
Figure 2. The schematic diagram of the software and hardware system for recording experimental images on board of an unmanned aerial vehicle.

Software part of the system consist of the two parts. First part is a client software on the Raspberry Pi, realized on Python. The second part is a server software. It is working on personal computer and is realized on C#.

As mentioned above, the main task of the system is to transfer images to a personal computer. However, the Raspberry Pi CM 3 module has only USB 2.0 ports onboard, so the theoretical maximum data transfer rate is 480 Mbps. In reality, the maximum achievable speed is much lower and limits at 100÷200 Mbps. Additional encoding of camera images to reduce their size and increase their transmission rate causes quite large delays. Thus this approach is not suitable for the task given.

Therefore, in the software two operating modes for image transfer were realized. The first mode provides visual evaluation of the resulting images. It is used to adjust focus, align mounts and make overall image quality assessment. In this mode the minimum resolution of 640×480 pixels is used. It allows to receive images in real time. The second mode is used for capturing images for measurements. In this mode resolutions are raised up to 2592×1944 pixels. Frames are saved locally on the system and then transferred to personal computer with delay.

Figure 3. The screenshot of the server software for developed system.
Measurements of the surface deformation were performed using the Image Pattern Correlation Technique (IPCT) [7]. This is a modern optical-television method for measuring strain, based on digital image processing. The algorithm of the method includes the following stages:

- application of the background pattern (a special pattern, which is recorded by digital video cameras) on the surface under investigation (on the model of the deformable wing);
- registration of the background pattern image in the initial state of the investigated surface (reference image);
- registration of the background pattern image when the surface is deformed (measuring image);
- cross-correlation processing of the obtained images: the reference and measurement images are divided into corresponding rectangular areas (8–64 pixels in size), for which the correlation function is calculated;
- finding the maximum of the correlation function for all the corresponding pairs of areas;
- the obtained vector displacement field allows to measure the deformation of the entire surface.

To measure 3D deformations, two video cameras are required, for each of which the above processing is performed. Data on the mutual arrangement of two cameras will allow reconstructing from two two-dimensional fields of two-dimensional vectors one two-dimensional field of three-dimensional vectors characterizing the 3D deformation of the investigated surface [8].

3. Laboratory tests of the developed system

Laboratory tests were performed to determine the efficiency and characteristics of the system. A fixture for the system was developed to mount it on board. It was printed on a 3D printer and used for installation in the laboratory (figure 4).

![Figure 4. The model for mount the system on board of the aircraft which was used for installation in the laboratory.](image)

A test bench [9, 10] for determining the error of photogrammetric methods was used. It is based on the simple idea to use a surface whose deformation occurs in a given way (an imitator of a deformable surface) and a high-precision optical sensor which can precisely measure surface deformation. Difference in the results obtained by sensor and by photogrammetric method allows to estimate the absolute error of the developed method within the scope of the error of the optical sensor. To measure the entire surface by one sensor, linear displacement modules with stepper motors were used. The sensor measures the distance to the surface at points, forming the grid with defined step, by moving above the surface in two perpendicular directions.
The imitator of the deformable surface consists of an aluminum base and several servos fixed on it. Each servo is rigidly connected to a section of a flexible plate located above the servos. The plate acts as a deformable surface with the maximum area of $380 \times 380 \text{ mm}^2$. The maximum number of servos is 16. Changing the position of the servo arm leads to a proportional displacement of the plate part above it in the vertical direction. The amplitude of the displacements for each servo is $\pm 25 \text{ mm}$. The imitator was used for modeling wing during the flight. The size of the imitator surface exactly matches the size of the wing on an unmanned aerial vehicle.

The module for measuring the distance to the surface consists of two linear displacement modules perpendicular to one another and an optical sensor. The optical sensor LS5-40/50 “NPP PRIZMA” measures distance based on the triangulation of the laser beam reflected from the measured surface. Sensor has a resolution of 0.001 mm and an error of less than 0.075 mm in the range of distances of 50 mm and the minimal distance to the sensor of 40 mm. The spot size of the laser beam of the sensor in the middle of the measurement range is 175 $\mu\text{m}$ and does not exceed 300 $\mu\text{m}$ in the entire range.

The software part is designed to control the entire test bench as a whole: setting the positions of the servos (deformation of the object) and displaying the results of the distance measuring unit to the surface using a graphical interface.

Examples of vector fields after processing experimental images from laboratory test for two cameras are presented in figure 5 along with corresponding results obtained with optical sensor.

![Figure 5](image)

**Figure 5.** Examples of vector fields after processing experimental images from laboratory test for two cameras (a) and (b) and corresponding measurement obtained with optical sensor (c).

4. **Conclusions**

The paper presents an approach to creating a flight laboratory for the development and debugging of optical flight test methods based on digital image processing. The cost-saving flight laboratory is based on an unmanned vehicle with a wingspan of 1.7 m. This allows conducting measurements in conditions very close to real in-flight tests: an increased level of vibration, the influence of aerodynamic loads and flight parameters on the deformation of the airframe, strong exposure to the Sun, etc.

To conduct studies of deformations of aerodynamic surfaces, a software and hardware system for recording experimental images on board of an unmanned aerial vehicle was developed. The system is based on a “Raspberry Pi CM 3 Lite” single-board computer, a “StereoPi” expansion card [6], and two digital video cameras. The main tasks of the system are capturing images from the cameras and
transferring them and corresponding flight parameters (altitude, speed, acceleration) to a personal computer wirelessly. The software part of the system consists of two parts: the client software on the Raspberry Pi, implemented on Python, and the server software on personal computer, implemented on C#.

Laboratory tests were performed to determine the efficiency and characteristics of the system. A test bench, developed earlier for determining the error of photogrammetric methods, was used. Results obtained with developed system and photogrammetric method were compared with the results of high accuracy optical sensor. The results of these tests confirmed system performance. The next stages of work will include laboratory tests to determine the accuracy characteristics, as well as the first flight tests of the developed system.

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