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A calibration trilogy of monocular-vision-based aircraft boresight system

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ABSTRACT

Aligning the orientation of Mounting Bases (MB) of sensors/weapons relative to the aircraft's reference datum, namely aircraft boresighting, is an important but tough task in aircraft assembly. A prototype MOnocular-Vision-based Aircraft Boresight (MOVAB) System, including a CCD camera and several Boresight Units (BU), is developed. The relative orientations of the MBs are obtained by capturing only one image of the BUs, which are mounted on the MBs. A BU is devised including a Visual Target Panels (VTP) with Infrared Light Emitting Diodes (ILED) as targets, an adapter which represents the MB and a bracket which bridges the VTP and the adapter. Since the camera of the MOVAB has a large working volume (i.e. large field of view and large depth of field), it is hard to make a calibration object large enough to guarantee the camera calibration accuracy. To this end, a new camera calibration method is proposed, which is based on the images taken from multiple perspectives of a 3D virtual calibration target generated with the aid of a coordinate measuring machine. The exact positions of the ILEDs on the VTP are calibrated based on the multiple view geometry principle. To recover the absolute metric of the layout of the target points, two auxiliary target points with known separation are constructed by means of accurate movement and are incorporated in the photogrammetry process. A concise yet effective procedure is proposed to calculate the relative attitude between the VTP and the adapter. It only needs to move the BU along two perpendicular lines and take images. The trio calibration is experimentally validated, and the aligning result from the MOVAB is compared to that a high-precision laser tracker.

1. Introduction

Modern military aircrafts are usually equipped with a variety of weapons and sensors such as inertial navigation unit, forward looking infrared, attitude heading reference system, and head up display. The proper relative orientations alignment of Mounting Bases (MB) of these sensors/weapons relative to the aircraft's principal datum reference is crucial to weapon delivery and flight control stability. Alignment errors reduce the accuracy of aiming and the probability of attacking success. The procedure for precisely aligning the orientations of these weapons/sensors is known as boresighting [1–3].

Boresighting has practically been an expensive and time-consuming task. The most widely used traditional boresighting is based on a target board positioned at some distance from the aircraft. The aircraft needs to be jacked and horizontally leveled into a known attitude with respect to the target board. A borescope or laser pointer is placed in a sighting fixture located at the sensor/weapon station. The deviation between the station sighting line and the anticipated position of that station on the target board is measured to determine whether the station is properly aligned or not. The target board method is conceptually simple, but has a number of limitations. The equipment is big and bulky, and the aircraft must be jacked and leveled, thus the task is laborious and time-consuming. Theodolites and laser trackers can also be used to carry out boresighting, while these methods typically require the aircraft to be jacked and leveled as well. Besides these commonly used methods, some other boresighting techniques are reported. Jaklitsch et al. [1] described and analyzed a boresighting system based on the inertial measurement technology. Cabib et al. [2] presented a number of implementations of boresight testing systems specifically designed for airborne mounted pods with Electro-Optical instrumentation such as laser designator, FLIR, and CCD camera.

Alternatively, we develop a MOnocular-Vision-based Aircraft Boresight (MOVAB) system, which can measure the attitudes of the MBs relative to the reference datum by capturing only one image of Visual Target Panels (VTP) of the Boresight Units (BU) fixed on the MBs. The MOVAB mainly consists of a CCD camera and a number of specifically designed BUs. The BUs are located on the Sensor/Weapon stations as well as on the datum structure which represents the aircraft reference coordinate system. The camera stands at a certain distance from the airplane and capture only one image of the visible parts of the BUs.

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With the one image taken, the boresight system is able to output in real time the yaw, pitch and roll angles of the sensor/weapon stations relative to the reference datum.

The monocular vision based boresight system is portable and easy to operate. There are no alignment requirements for the camera when it images the VTPs. In addition, the system is efficient since it can simultaneously obtain the orientations of multiple sensor/weapon stations with respected to the aircraft datum. Above all, there is no need to jack/ level the airplane during the boresighting. For vision-based measurement equipments, system calibration is one of the most important issues. It directly determines the performance and accuracy of the system. Since the camera of MOVAB is in charge of simultaneously monitoring multiple VTPs installed on different positions of an aircraft, the camera is required to work with a large-extent field-of-view. More specifically, the working volume of the camera should reach more than 10 meters on all sides. In this situation, accurate calibration of the camera and the visual targets is even difficult and crucial.

In this paper, we introduce the monocular-vision-based boresight system, focus on the system calibration problems and analyze the difficulties involved. A trio innovative approach is proposed to realize the system calibration, which proves to be of good performance. The rest of the paper is organized as follows. Section 2 provides a review on conventional techniques. Section 3 briefly describes the MOVAB's working principle. In Section 4, we devise a camera calibration with large working volume to accurately calibrate the camera intrinsic parameters and lens distortion coefficients. The VTP calibration is presented in Section 5. A simple yet effective procedure of the BU calibration is introduced in Section 6. The proposed trio calibration is verified by real and comparative experiments in Section 7 and the conclusion is drawn in Section 8.

2. Related work

Camera calibration is used to quantitatively establish the mapping model between the 3D space and the image plane. Researchers have proposed various types of calibration methods to determine the parameters involved in the model. Only if the parameter matrix in the pinhole camera model is calibrated, it is possible to solve the calibration problem by using simple linear techniques, such as the one suggested in Ref. [4]. If the lens distortion coefficients are considered, it is necessary to resort to more complex nonlinear optimization [5]. Readers are referred to [6] for a comparative review of the most adopted calibration methods.

To achieve higher camera calibration accuracy, the precise knowledge of the calibration reference object is necessary. In terms of different kinds of reference objects, they can be categorized into one-dimensional (1D) [7], two-dimensional (2D) [8], and three-dimensional (3D) [9] ones. The choice of an appropriate calibration object is often a tradeoff between the required calibration accuracy and the manufacturing complexity of the calibration object [10]. In general, 3D calibration objects grant a more stable and precise calibration due to sufficient depth information in the target, which limits the interplay between the estimation of the focal length and the lens distortion. In addition, the size of a 3D calibration object should be similar to the camera's working wide and depth (i.e. working volume) to reduce the error distribution throughout the whole working space as much as possible.

Unfortunately, building an accurate 3D calibration object with large size is very difficult, for it requires an expensive machining and needs a remarkable amount of effort for maintenance and verification. Xu et al. [11] leveraged a moving end of Coordinate Measuring Machine (CMM) to carry an ILED target to a series of 3D positions in order to form a virtual 3D calibration pattern. This method to some extent has solved the problem of hard manufacture of 3D calibration object. However, for the camera calibration with large working volume, the virtual calibration pattern generated by CMM or any other high precision moving devices is typically much smaller than the required size, it will lead to relatively low calibration and measurement precision. Moving devices with long travel distance is expensive and hard to develop, typically has a declined accuracy level, which adversely affects the calibration accuracy. Chen et al. [12] presented a method to calibrate cameras in a wide area by freely waving an identifiable point (target) in front of all cameras to create a virtual object. Due to its dynamic environments, the calibration error of their methods is up to 10 pixels. Kurillo et al. [13] extended Chen's method by using the virtual calibration object defined by two moving LED markers with known distance. The calibration error is remarkably decreased below 0.4 pixels, but it still cannot meet the MOVAB precision requirement which needs less than 0.1 pixels. On the other hand, unlike the MOVAB, which is able to cover a large working volume with a single camera, multiple cameras are used by Chen and Kurillo to constitute a network to cover the whole area, where every single camera just has a normal working volume. Chen and Kurillo just performed the calibration for external camera parameters.

More recently, Liu et al. [14] proposed a method for camera calibration with a large field of view. They used several small planar calibration objects combined to cover the whole measurement area with a little change of depth of field. However this method cannot work in our case, for images of the targets will change a lot in a large depths of field, which will cause large error of targets' exacting and locating. Moreover, if ILEDs are used as the targets of planar calibration object, the targets cannot be assured coplanar by manufacturing, which will be experimentally proved in our paper.

3. An overview of the MOVAB's working principle

As shown in Fig. 1, the MOVAB makes use of only one camera to take only one image of the BUs fixed on the Sensor/Weapon stations as well as on the aircraft datum structure to obtain the attitude parameters of the sensors/weapons relative to the reference datum. For the sake of discrimination, the BU installed on the datum structure is also called Reference BU (RBU) in some context. Since the sensor/weapon stations, as well as the datum structure of the aircraft are typically hidden inside the aircraft, the BUs adopt the form as that shown in Fig. 2, which consists of three different components: a Visual Target Panels (VTP), an adapter and a bracket. The adapter directly interfaces with the mounting base of sensor/weapon station or the datum structure. The VTP, which is outside of the aircraft, is the visual object observed by the camera. The bracket bridges the adapter and the VTP. To make the BUs adapt to the specific local environment, the adapter and bracket of each BU are usually in different style and size.

The MOVAB takes Infrared Light Emitting Diodes (ILED) as targets, which can be regarded as ideal pointolites. The brightness of each ILED can be independently auto-adjusted in real time by a specified controller, which can keep the targets uniformly illuminate in a large working volume (i.e. large field of view and large depth of field). Each VTP is embedded with n ILEDS ($n = 8$ in our implementation). The camera is equipped with an infra-red-pass filter, thus only the ILEDs in the scene can be imaged as light spots in the image. The boresight software controls the camera to take a image and processes the captured image to evaluate the relative orientation in real time.

As shown in Fig. 3, the ILED is an electronic element with a very small light-emitting unit in the center. Then it is wrapped by a base in order to be assembled into a VTP. Unlike some other targets which can be precisely determined either by manufacturing by contact CMM measuring, the exact central position of an ILED cannot be precisely determined. Therefore, we propose a non-contact vision-based method, which called VTP calibration, to measure the exact 3D coordinates of the ILEDs' centers.

To conveniently describe the MOVAB's principle, we define four cartesian coordinate frames as shown in Figs. 1 and 2, the camera coordinate frame $O_c{-}X_cY_cZ_c$ ({CAM}), the VTP coordinate frame $O_t{-}X_tY_tZ_t$ ({VTP}), the adapter coordinate frame $O_a{-}X_aY_aZ_a$ ({ADP}),