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Remote-controlled flexible pose measurement system and method for a moving target in wind tunnel

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Abstract The measurement of position and attitude parameters for the isolated target from a high-speed aircraft is a great challenge in the field of wind tunnel simulation technology. This paper proposes a remote-controlled flexible pose measurement system in wind tunnel conditions for the separation of a target from an aircraft. The position and attitude parameters of a moving object are obtained by utilizing a single camera with a focal length and camera orientation that can be changed based on different measurement conditions. Using this proposed system and method, both the flexibility and efficiency of the pose measurement system can be enhanced in wind tunnel conditions to meet the measurement requirements of different objects and experiments, which is also useful for the development of an intelligent position and attitude measurement system. The position and the focal length of the camera also can be controlled remotely during measurements to enlarge both the vertical and horizontal measurement range of this system. Experiments are conducted in the laboratory to measure the position and attitude of moving objects with high flexibility and efficiency, and the measurement precision of the measurement system is also verified through experiments.

1. Introduction

The capability for military aircraft in flight to release external stores, such as weapons and auxiliary fuel tanks, when necessary is highly important. However, because of the interaction between the aerodynamic environment and the dynamic characteristics of the external stores, the released stores may collide with the aircraft, threatening the performance of the aircraft and the safety of the pilot.[1,2]

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Simulative store separation experiments in wind tunnels provide valuable reference for the layout design and release parameters of the store. Among many research methods, the free drop method is one of the most typical experimental methods for store separation simulations in wind tunnels. The free drop method, with which the external store was ejected from the aircraft and fell down freely, and high-speed cameras were used to capture the trajectory of the external store, was widely used in simulative experiments for flight testing. However, since wind tunnel models usually have a large range of movement and rotation at high speeds and the measurement environment is more complex, traditional measurements fail to correctly measure their pose information. Photogrammetry (or videogrammetry) is a non-contact and efficient method for the measurement of model deformation, dimensions, and the position and attitude parameters of moving targets. Especially in complex measuring conditions, such as the underwater environment, outer space, and wind tunnels, photogrammetry is widely used. Therefore, pose measurement in wind tunnels based on vision measurement is of great importance.[3,4]

NASA Langley Research Center (LaRC) designed a multi-camera videogrammetric system to measure model attitude in hypersonic facilities.[5] The technique utilized processed video data and applied photogrammetric principles for point tracking to compute the model's position, including pitch, roll and yaw variables. Liu et al. proposed a position and attitude measurement method based on binocular vision for high-speed targets in wind tunnels. They performed measurement experiments for testing the release capability of aircraft in a wind tunnel and obtained high-precision results.[6] They then, in a subsequent paper,[7] proposed a position and attitude measurement method for wind tunnel models based on laser-aided vision technology. By using laser strips instead of reflective markers, a high-intensity light installed outside the wind tunnel is not required, which greatly improves the quality of the images because most of the redundant light reflected from the observation window can be avoided. In addition, other studies by the same authors proved that the use of self-luminous markers encoded inside the model helped to improve the brightness of image features and avoid the use of external lights.[8] Jia et al. proposed a position and attitude measurement method based on binocular vision. They obtained both the position and attitude of high-speed flying models; the measurement precision of displacement was less than 0.16 mm, that of pitch and yaw angles was less than 0.132°, and that of roll angle was 0.712°.[9] Others also studied intelligent and efficient measurement methods based on monocular vision. Graves and Burner developed an intelligent videogrammetric wind tunnel measurement system consisting of a digital CCD camera, a frame grabber, and a Personal Computer (PC).[10] The system can be useful and usable in measuring the deformation and attitude parameters of different models. The system features advanced pattern recognition techniques to improve automated location and identification of targets placed in the wind tunnel model, which greatly improves the intelligibility of visual measurements. Murray conducted experiments on position and attitude measurement of aircraft stores released from a payload bay at supersonic speeds in a trisonic wind tunnel. The store model has two collinear circular markers attached as image features. During the separation, a high-speed camera is utilized to acquire real-time images of the model, and the trajectory of the model, as well as its pitch and yaw angles, can be calculated based on the 2D information in those images.[11] Tanno et al. proposed a single camera method for the measurement of the complete 3D displacements and rotations of a free-flying model in a shock tunnel.[12] Among this research, the vertical and horizontal measurement ranges of most of the systems are small. Additionally, these systems are not flexible. In addition, the precision of the monocular vision pose measurement system is low.

As the number of internal and external model types increases and the required range of measurement during pose measurements becomes larger in high-production wind tunnels, it is important to improve the efficiency and flexibility of the position and attitude measurement. In this paper, we turn our attention to the development of a flexible position and attitude measurement technique.[13,14] Based on the precise location of the markers on the object surface, the position and attitude of the moving object can be computed using a single camera without knowing the camera focal length; therefore the camera focal length can be readjusted to ensure that high-quality images of different objects can be obtained during the measurement. Additionally, the camera orientation can be readjusted based on a transformation between the world coordinate system and the reference coordinate system in which the camera moves to ensure that the camera can obtain a proper field of view. Therefore, a flexible and efficient position and attitude measurement system is established for modern wind tunnels.

This paper is organized as follows: Section 2 introduces the overall measurement scheme for a flexible position and attitude measurement method and system for moving objects; Section 3 introduces the image acquisition and processing method in the wind tunnel; Section 4 introduces the flexible measurement principle without camera recalibration when the camera focal length or the camera orientation changes; Section 5 introduces the method for computing the position and attitude parameters; Section 6 describes the measurement experiments for moving objects in the laboratory as well as verification experiments for the measurement precision of the established system; Section 7 presents the study's conclusions.

2. Flexible position and attitude measurement system and method

2.1. *Vision-based pose measurement method for wind tunnel models*

The principle of the flexible measurement method based on a single camera is shown in Fig. 1. CCS is the camera coordinate system, and CMR is camera motion reference. TCS is the target coordinate system, and WCS is the world coordinate system. $[\boldsymbol{R}_{\mathrm{ow}} \quad \boldsymbol{T}_{\mathrm{ow}}]$ is the transformation matrix between the TCS and the WCS. $[\boldsymbol{R}_{\mathrm{o}} \quad \boldsymbol{T}_{\mathrm{o}}]$ is the transformation matrix between the TCS and the CCS. $[\boldsymbol{R}_{\mathrm{c}} \quad \boldsymbol{T}_{\mathrm{c}}]$ is the transformation matrix between the CCS and the WCS. Markers are first attached at known positions in a TCS established on the object, where the object's center of mass is the origin of the coordinate system. The view and the position of the camera can be controlled by a remote-controlled system to make sure that the target is in the field of view of the camera. The images of the moving object are captured by the single-view camera for milliseconds. Next, each of the markers is detected in the

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