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High-precision pose measurement method in wind tunnels based on laser-aided vision technology

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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. In this paper, firstly, an image acquisition method for small high-speed targets with multi-dimensional movement in wind tunnel environment is proposed based on laser-aided vision technology. Combining with the trajectory simulation of the isolated model, the reasonably distributed laser stripes and self-luminous markers are utilized to capture clear images of the object. Then, after image processing, feature extraction, stereo correspondence and reconstruction, three-dimensional information of laser stripes and self-luminous markers are calculated. Besides, a pose solution method based on projected laser stripes and self-luminous markers is proposed. Finally, simulation experiments on measuring the position and attitude of high-speed rolling targets are conducted, as well as accuracy verification experiments. Experimental results indicate that the proposed method is feasible and efficient for measuring the pose parameters of rolling targets in wind tunnels.

1. Introduction

The pose measurement for models in wind tunnel experiments is widely required during the design and manufacture process of aircraft. Recently, characteristics of targets in the wind tunnel such as smaller volume, high-speed self-rotating motion, etc., have become a great challenge for pose measurement.[1–4]

Much work has been done on the pose measurement for wind tunnel models. NASA Langley Research Center (LaRC)[5] designed a standard package consisting of an accelerometer and several vibration isolation pads to measure the pitch attitude of wind tunnel models, and the accuracy of less than 0.01° could be obtained under smooth wind tunnel operating conditions. However, for rolling small targets, the measurement device proposed by LaRC was difficult to be installed inside the tested model. Besides, the roll and yaw attitudes could not be calculated. Optotrak™[6] developed a wind

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tunnel pose measurement device utilizing linear CCD cameras and infrared cooperating markers. Although the device was quite accurate and stable, the infrared cooperating markers were relatively big and a powerful light source was necessary, which caused the inability of measuring small models. NASA LaRC[7] also developed a pose measurement system based on binocular vision for wind tunnel models. The model images were captured continuously using two CCD cameras synchronously through the observing window. After measuring the 3D centroid coordinates of retro-reflection markers, the pose parameters of the wind tunnel model could be calculated. However, because the light was easily reflected to cameras by the thick glass of the observation window, the image quality was difficult to guarantee by using retro-reflection markers. In addition, the luminance and the space brightness uniformity of the images could be reduced in high-speed shooting conditions. Chen et al.[8] have proposed a pose measurement method for models in the wind tunnel based on stereo vision. The cooperating targets with two bi-directional laser beams are placed between two screen walls, then the 3D coordinates of the bi-directional laser beam markers are obtained utilizing the stereo vision measurement technology, and the pose parameter of the model is then calculated through the rotating and translation matrixes. This method has improved the measurement precision by scaling the variation of the target. Fan et al.[9] proposed an attitude angle and position tracking system for indoor carrier based on integrated navigation fusion strategy of integrated navigation fusion strategy (INS)/ultra wide band (UWB). They used feedback correction method to integrate the two subsystems, INS and UWB. Then, optimal comprehensive and filtering strategy based on fuzzy adaptive Kalman filtering (FAKF) is introduced to realize the data fusion of two subsystems. Though, the position and attitude angle parameters of the mobile carrier can be obtained in real time. However, when it comes to small rolling high-speed targets in the wind tunnel, UWB technology can hardly be applied in the complex measuring environment. Royal aircraft manufacturing company[10] designed a combined pose measurement system (MAM). By using measurement system, they were able to measure four pose parameters of a model in the wind tunnel simultaneously, that is the pitch angle, roll angle, yaw angle and geometry offset of the model's geometric center. Three orthorhombic servo accelerometers were utilized to measure the pitch angle and roll angle of the target. In addition, the yaw angle and horizontal offset of the model's geometric center can be measured by photoelectric sensors. Results show that the measurement error of the yaw angle is less than 0.5°. However, the measurement accuracy is large which cannot satisfy the measurement requirements in the wind tunnel. Besides, there is not enough room for mounting accelerometers inside the model, thus this method is not suitable for small targets used in this paper. Crites[11] from McDonnell Douglas aircraft manufacturing company developed a polarized laser goniometer used to measure the angle of attack of models in the wind tunnel. They used two photoelectric detectors to detect transmitted intensity of two polaroid, respectively. Then the angle of attack can be calculated by Malus Law according to the relationship between the angle of attack and transmitted intensity. Though the incident light intensity fluctuation would not lead to instability of measurement results, the interference of lighting source cannot be avoided. Moreover, the method can only be used to measure the angle of attack of the model and the measuring range is relatively narrowed. Thus, it cannot meet the calculation requirements of pose measurement of models in this paper. Cheng et al.[12] developed a position and attitude vision measurement system for drop test slender models in wind tunnel conditions. Unlike traditional binocular measurement methods, the system is based upon image matching technique between the 3D-digital model projection image and the image captured by cameras. This system presents a creative and effective thinking of pose measurement for wind tunnel models. Sun et al.[13] presented a binocular vision measurement technique to measure models' angle of attack in a wind tunnel and the results are of high precision. Liu et al.[14] presented a high-precision pose measurement method for auxiliary fuel tank models in the wind tunnel based on self-luminous units. This method is capable of achieving brighter image features and higher signal to noise ratio of the images. However, it is hard to install self-luminous units in small-sized objects because of their large volume.

Many scholars and research institutions have made outstanding contributions to pose measurement for wind tunnel models. However, in wind tunnel environments with a large field of view, the pose measurement technology for small models with high-speed rolling movement is far from perfect. Thus, a stereoscopic vision pose measurement method based on structured light for high-speed rolling wind tunnel models is proposed in this paper, solving the problem of pose measuring for high-speed wind tunnel models in the complex environment. Firstly, to achieve objects' pose measurement in complex wind tunnels, a high-speed binocular vision measurement system has been built. Afterwards, based on the predicted spatial trajectory of the model, lasers are properly distributed onto the model surface, and images of the model are captured by two high-speed cameras. Then, the sub-pixel center line of the model feature corners and 3D coordinates of the feature points can be obtained after the laser stripe is extracted and matched. Eventually, the pose parameters can be obtained through coordinate transformation.

2. High-speed image acquisition method

2.1. High-speed image acquisition method based on laser line structured light

Difficulties of the position and attitude measurement for small high-speed isolates in the complicated wind tunnel environment are as follows: (a) The high-speed and high-precision image acquisition is difficult to realize due to some factors, such as the complex wind tunnel environment with small and dark experimental space, high surface reflectance of the model and observation windows with strong reflection; (b) The marker tracking in the process of position and attitude measurement is difficult to achieve due to the fact that the small-model has a high separation speed with rolling movement in a short separation time.[15,16]

Currently, there are two main image acquisition methods for wind tunnel targets. One of them is the method based on reflective markers with retro-reflection material and LED source surrounding the lenses. However, in wind tunnels with thick observation windows, most of the light would be reflected back by the window. Another way to acquire image is using infrared self-illumination markers. However, large