Optics and Lasers in Engineering 112 (2019) 46–52

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng

# Non-scanning measurement of position and attitude using two linear cameras

Jidong Liu, Qinwei Ma, Haibin Zhu, Shaopeng Ma*

*School of Aerospace Engineering, Beijing Institute of Technology, Beijing 100081, China*

A R T I C L E I N F O

*Key words:*
Position and attitude measurement
Linear camera
Five-line plane target
One-dimensional image
Cross-ratio invariability

A B S T R A C T

Most photogrammetry-based object position and attitude measurement systems use area cameras for two-dimensional (2D) image acquisition. However, the large volume of 2D images provided by area cameras limits the image capture speed, thus preventing the application of such methods to some high-speed measurements. Linear camera-based systems cannot be used to obtain real-time position and attitude parameters of non-specially designed objects because of scanning imaging and optimisation requirements. In this work, a novel position and attitude measurement method based on linear cameras was proposed. The position and attitude of objects can be obtained by analysing simultaneously recorded images of a specially designed five-line plane target using two calibrated linear cameras. This method can be used to carry out high-speed measurement of position and attitude parameters because no scanning imaging is required. In the present paper, we introduce the principle of this method, present verifications based on virtual and actual experiments, and analyse the main factors that affect measurement error.

## 1. Introduction

Position and attitude measurement (PAM) refers to obtaining objects' three-dimensional (3D) location, attitude and variation. Specifically, PAM requires acquiring a translation vector $T$ and rotation matrix $R$ between the reference and object-attached coordinate systems. PAM is critical in scientific areas such as automatic navigation, robot vision, and dynamics analysis. In general, there are two types of PAM methods: contact measurement based on velocity or acceleration sensors [1] and non-contact measurements based on photogrammetry [2–4]. The former method introduces extra mass to objects, changing their intrinsic dynamic properties. In contrast, photogrammetric methods [5,6] have the advantages of not requiring contact, providing a wide measurement range, and being simple in measuring implementation. Therefore, photogrammetric methods have become popular for PAM. If using these methods, object images must be acquired using digital cameras. The coordinates of features on the object (such as markers or lines) can then be extracted using image processing algorithm. The reference coordinates of these features can be calculated by combining the internal and external parameters of a digital camera and its imaging principle. Finally, spatial parameters can be obtained with the known reference coordinates of features on the object.

In accordance with the number of camera used, photogrammetric measurement systems can be classified as stereo or monocular. At least two cameras obtaining object images from different directions are required for stereo vision systems [4]. The positions of feature points on the object are then obtained by intersecting the cameras' optical centres with the corresponding points in different images. The spatial positions of the object can be obtained based on the known coordinates of multiple points on the object. However, short baselines and narrow site layouts in many cases mean that only one camera can be used to observe the position and attitude of a measured object. In such monocular vision systems, the intersection condition cannot be fulfilled. Therefore, supplemental information is required to obtain a unique solution. For example, in the Perspective-n-Points problem [7], the known spatial relationship between multiple-feature points is often used as supplementary information. The foregone structure of object is often employed as supplemental information for customised target and contour matching [8,9]. In some cases, the given trajectory of the camera, together with the smoothness of the motion of a point in space–time, is considered as supplemental information when only the point's position is required [10].

The examples above use 2D images as raw data and area cameras as image capture devices. However, in special PAM applications, such as real-time or high-speed measurement, data acquisition and processing speed of area camera might be restricted by the large volume of 2D image data. Therefore, some specialists have proposed photogrammetric methods based on linear cameras. A linear camera is a special image acquisition device with only one column or row of photosensitive units. Compared with an area camera, they produce smaller data vol-

* Corresponding author.
*E-mail address:* masp@bit.edu.cn (S. Ma).

https://doi.org/10.1016/j.optlaseng.2018.08.019
Received 15 May 2018; Received in revised form 21 August 2018; Accepted 28 August 2018

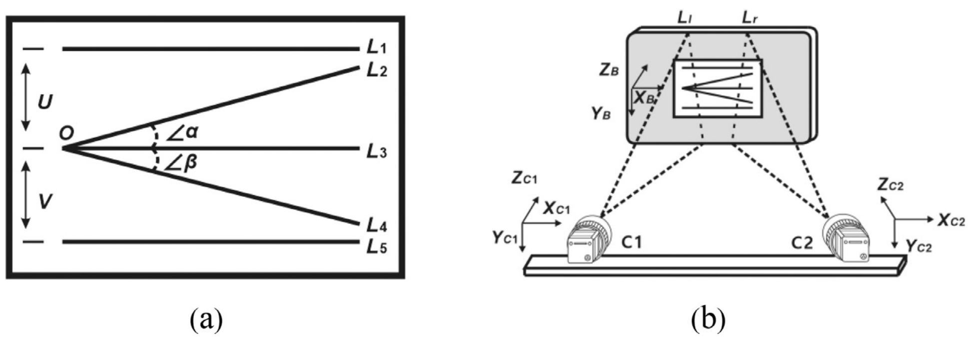


**Fig. 1.** Schematic diagram of the PAM system: (a) five-line plane target and (b) system layout.

ume at higher acquisition rates. Because there is only one column/row of image data, the scanning imaging technique is often used in linear camera-based PAM systems; that is, the measured object rapidly passes through the viewing plane during measurement and the obtained 1D images are merged into a 2D image along the time axis for further analysis [11–13]. For example, Watanabe et al. [12] used a linear camera to measure a small section of the trajectory and posture of a golf club head. Because of the requirement for scanning imaging, such methods lose time resolution and are difficult to apply in real time. To avoid scanning imaging, it is essential to optimise the measuring procedure, light path, or measured object. Li et al. [14] achieved PAM based on three linear cameras by altering the light path. Specifically, point light sources were installed on the object and cylindrical lens were used to transform point light sources into line light sources. Horaud et al. [15] and Luna et al. [16] tried the measurement concept without changing the optical path; however, Horaud's method had to accurately move the object and image it at least three times and in Luna's method, the measured object had to be modified into a complex 3D structure. All the above linear camera-based methods have limitations and cannot be used in real-time PAM of non-specially designed objects.

This paper proposes a novel PAM method based on linear cameras and a specially designed five-line plane target. With this plane target, neither scanning imaging nor optimisation is required, only two linear cameras are needed, and the 6-degree of freedom (6-DOF) position and attitude parameters $R$ and $T$ of the object can be obtained through a single data acquisition. In the present paper, the specially designed five-line plane target is introduced in Section 2, in which the mathematical principles of extracting 6-DOF position and attitude parameters from 1D images is detailed. In Section 3, a virtual experiments is first presented to validate the correctness of the proposed method; then, the main factors affecting PAM accuracy are analysed based on a series of virtual experiments; actual experiments verifying the validity of the proposed method are also presented, and recommendations for the measurement layout are summarised. Finally, concluding remarks are made in the final section.

## 2. Principle

A specially designed five-line plane target, shown in Fig. 1(a), is used as an auxiliary target to help obtain position and attitude parameters. Among the five straight lines $L_1$–$L_5$, there exists $L_1$ // $L_3$ // $L_5$; the distances between them are defined as $U$ and $V$ respectively. $O$ is the intersection point of lines $L_2$, $L_3$, and $L_4$, and the angles between these three lines are defined as $\alpha$ and $\beta$, respectively. The plane target is attached to the measured object and imaged using two calibrated linear cameras $C_1$ and $C_2$ (shown in Fig. 1(b)). The internal and external parameters of cameras $C_1$ and $C_2$ are given in advance. The view planes of $C_1$ and $C_2$ intersect with the plane target at $L_l$ and $L_r$, respectively. $X_BY_BZ_B$ is defined as the coordinate system of the plane target, which is fixed with the object. $X_{C1}Y_{C1}Z_{C1}$ and $X_{C2}Y_{C2}Z_{C2}$ are the local coordinate systems of the two cameras, respectively. As illustrated in Fig. 1(b), the PAM of

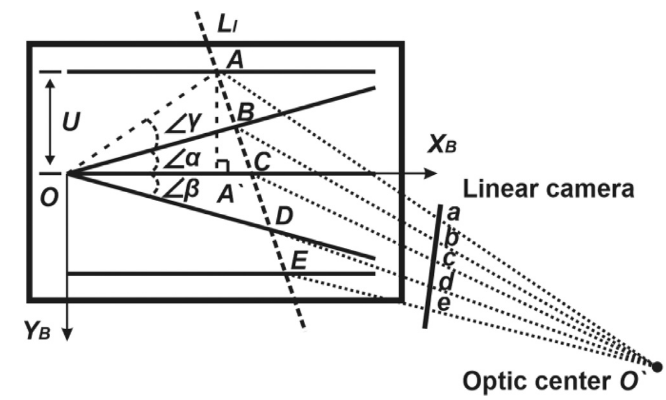


**Fig. 2.** Imaging the five-line plane target.

the plane target can be converted to solve the relative relation $R$ and $T$ between $X_BY_BZ_B$ and one camera coordinate system.

The above measurement can be achieved in the following three steps: 1) measuring the coordinates of $L_l$ and $L_r$ in $X_BY_BZ_B$, respectively; 2) solving the coordinates of $L_l$ in $X_{C1}Y_{C1}Z_{C1}$ and $L_r$ in $X_{C2}Y_{C2}Z_{C2}$, respectively, then transforming $L_r$'s coordinates from $X_{C2}Y_{C2}Z_{C2}$ to $X_{C1}Y_{C1}Z_{C1}$ (the coordinates of both $L_l$ and $L_r$ in $X_{C1}Y_{C1}Z_{C1}$ are known); 3) selecting any $N$ ($N \geq 3$) non-collinear points form $L_l$ and $L_r$'s intersection points with the five lines on the plane target; the translation vector $T$ and rotation matrix $R$ between $X_{C1}Y_{C1}Z_{C1}$ and $X_BY_BZ_B$ can be solved with the resolved coordinates of these points in both $X_{C1}Y_{C1}Z_{C1}$ and $X_BY_BZ_B$.

First, taking the solution of $L_l$ as an example, as illustrated in Fig. 2, if a linear camera is used to image a five-line plane target, line $L_l$ between the view and target planes intersects with lines $L_1$–$L_5$ at points $A$–$E$. Points $a$–$e$ are the corresponding related image points. To determine the coordinates of $L_l$ in $X_BY_BZ_B$, it is necessary to solve two of points $A$–$E$ based on known information from the five-line plane target and the image coordinates of points $a$–$e$.

According to points $A$–$D$ and the corresponding image points $a$–$d$, there exists

$$CR(A, B; C, D)=\frac{D_{AC} \times D_{BD}}{D_{BC} \times D_{AD}}, \tag{1}$$

where $CR$ represents the cross-ratio of points $A$–$D$ in the viewing plane and $D_{AC}$, $D_{BD}$, $D_{BC}$, and $D_{AD}$ represent the distance between the corresponding two points, respectively. In the image plane, the cross-ratio of image points $a$–$d$ can be expressed as

$$CR(a, b; c, d) = \frac{D_{ac} \times D_{bd}}{D_{bc} \times D_{ad}}. \tag{2}$$

According to the cross-ratio invariability law [17], there exists

$$CR(A, B; C, D)=CR(a, b; c, d) = \frac{\sin\angle AO'C \times \sin\angle BO'D}{\sin\angle BO'C \times \sin\angle AO'D}. \tag{3}$$