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Workspace measuring and positioning system based on rotating laser planes

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1. Introduction

As science and technology develop and the needs of large-scale engineering surveying practice increase, non-orthogonal coordinate system are established through combining angle and distance measurements to achieve large-scale precision measurement, such as geometric parameters measuring for large parts, structural checking, adjustment and assembly. Currently, large-scale space nonorthogonal coordinates system are usually including theodolite measuring system, laser tracking system, articulated coordinate measuring machine, digital photogrammetry system and iGPS (indoor Global Positioning System) as mentioned in [1].

The first iGPS inspired by GPS was developed in the 90s by the American Arcsecond company and has provided a new technical solution for large-scale precision coordinate measurement [2, 3]. In recent years, some universities and research institutions in China have done a great deal work about theoretical research and prototype experiments of iGPS. wMPS (workspace Measurement and Positioning System) is just such a system that researched and developed by Tianjin University [4].

Among the common systems mentioned above, theodolite system aims at the target point through optical alidade and obtains the coordinate value by reading angle scale. It has the advantages of wide rang and high accuracy but not a high degree of automation due to manual collimation. Laser tracking system requires a cat's eye reflector fixed on the target to work together. By tracking the reflected laser from the cat's eye, the target coordinates can be got. But under the condition of accurate measurement, laser tracking system doesn't allow visibility restriction, which lowers down the efficiency. wMPS is an angle intersection system similar to theodolite system, but somewhat different from it. The elementary unit of wMPS is composed of transmitters and receivers. Receivers are opto-sensors fixed on the points where needs to be surveyed such as the key points during aircraft parts assembly. Each of the transmitters sweeps two infrared laser beams continuously which are detected by the receivers and converted into time pulse by high speed timing circuit in order to get angle values. Point coordinates then can be determined through the intersection of a couple of angles. Unlike theodolite system and laser tracking system, wMPS has a high degree of automation and allows light bloking. In addition, the most significant characteristic of wMPS is that the accuracy will not descend as the measuring range enlarges.

This paper mainly describes the key technique of wMPS. The next section depicts the system configuration. Section three establishes the multiplane constraint model which is suitable for both setup and measuring. Section four is related to the adjustment calibration using in setup. Section five presents the experiment results and section six and seven discuss some error related issues and summarizes with some concluding remarks.

2. System configuration

In order to manage the system resources efficiently and carry out tasks parallelly, a double-decker architecture was designed as Fig. 1 shown. Four parts are included: transmitter, receiver, central control device and task computer.

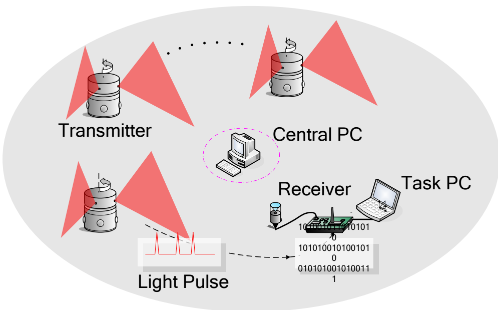

Fig. 1 System configuration

Before measuring, the position relationship parameters between transmitters should to be known and laser beam parameters as well. We call all these parameters system resources and the process to get these parameters setup process. Central control device is a central computer which is responsible for storing and managing the system resources. Task computer is used to get resources from central computer, process the receiver time signals, calculate and store the position of the receiver to execute different tasks such as tracking, adjustment and so on.

The structure of transmitter is shown in Fig. 2. The rotating head of the transmitter sweeps two fanned laser beams and the stationary body of the transmitter delivers a strobe with a single pulse to determine the system's zero-time. Both beams are inclined at an angle to the vertical and offset by an angle to one another. The inclined and offset angles determine the measuring range and the lever of angle error measured by single station.

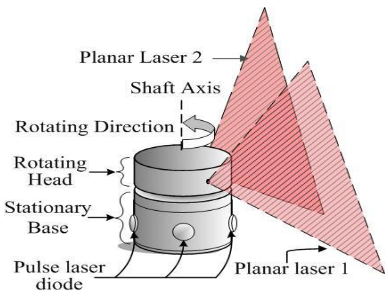

Fig. 2 Transmitter

The receiver, which distinguishes transmitters according to their different speeds ranging from 1000 to 3000 (r/min), is a photoelectrical sensor which can detect both the pulse signal and two laser beam signals at the time sequence as shown in Fig. 3 and send the time information to the control computer through wireless communication.

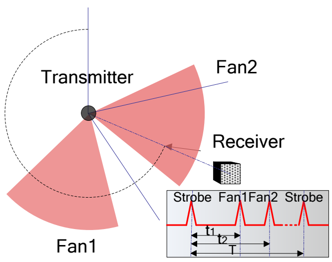

Fig. 3 Receiver signals

Fig. 4 is an illustration of the system application scenarios. The receivers are simplified into circle dot labeled on the surface of the survey object. They receive the light signal from the transmitters and send the time signal to task computer to calculate their positions.

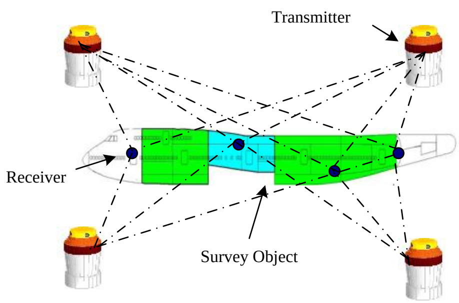

Fig. 4 Illustration of the application

3. Mulitplane constraint model

We abstract the model of measurement as Fig. 5. The local coordinate system of transmitter is defined like this: Z-axis is the rotation axis. Origin is the intersection of rotation axis and laser plane1. X-axis through the origin is on plane1 and perpendicular to Z-axis. Y-axis is determined according to the right-hand rule. The point P stands for the sensitivity centre of receiver which fixed on the surface of the object. Assuming that the transmitter is anticlockwise–revolving around the rotation axis at the speed of *w* (rad/s), the inclined angle of plane1 is ϕ_1 while the inclined angle of plane *2* is ϕ_2. The horizontal offset angle between two planes is θ_{off}.

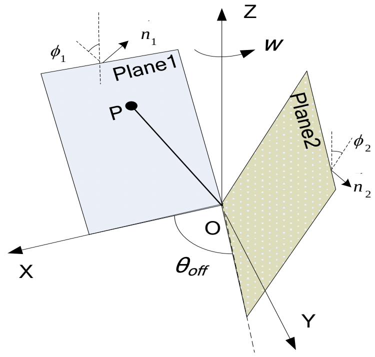

Fig. 5 Plane constraint mathematical model

According to that the normal vector of a plane is perpendicular to an arbitrary line on the plane, set the measured point coordinate to be *P*, the rotation and translation matrix between the local coordinate system of the *i*-th transmitter and the global coordinate system is $\left[R_i \quad T_i\right]$, thus in the global coordinate system, each transmitter has the following equation

$$R_i\, \vec{n}_{mt} \left[P - T_i\right] = 0 \quad (m = 1, 2) \tag{1}$$

In Eq. (1), R_i and T_i are the result of system setup using adjustment calibration. $\vec{n}_{mt}$ is the *m*-th plane normal vector of the *i*-th transmitter at time *t*. *P* is the unknown parameter for measured point. For $\vec{n}_{mt}$, we can get its values through the following procedure. According to the plane parameters, at the initial moment, the normal vector of plane *1* is

$$\vec{n}_{10} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi_1 & -\sin\phi_1 \\ 0 & \sin\phi_1 & \cos\phi_1 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ \cos\phi_1 \\ \sin\phi_1 \end{bmatrix} \tag{2}$$

While the normal vector of plane *2* is

$$\vec{n}_{20} = \begin{bmatrix} \cos\theta_{off} & -\sin\theta_{off} & 0 \\ \sin\theta_{off} & \cos\theta_{off} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi_2 & -\sin\phi_2 \\ 0 & \sin\phi_2 & \cos\phi_2 \end{bmatrix} \times$$
$$\times \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} = \begin{bmatrix} -\sin\theta_{off}\cos\phi_2 \\ \cos\theta_{off}\cos\phi_2 \\ \sin\phi_2 \end{bmatrix} \tag{3}$$

At time t_1, plane *1* passes through point *P*, the normal vector of plane1 becomes

$$\vec{n}_{1t} = \begin{bmatrix} cos\,wt_1 & -sin\,wt_1 & 0 \\ sin\,wt_1 & cos\,wt_1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \vec{n}_{10} = \begin{bmatrix} -sin\,wt_1\,cos\,\phi_1 \\ cos\,wt_1\,cos\,\phi_1 \\ sin\,\phi_1 \end{bmatrix} \quad (4)$$

Similarly, at time t_2 when plane *2* passes through point *P*, the normal vector of plane *2* comes to be

$$\vec{n}_{2t} = \begin{bmatrix} cos\,wt_2 & -sin\,wt_2 & 0 \\ sin\,wt_2 & cos\,wt_2 & 0 \\ 0 & 0 & 1 \end{bmatrix} \vec{n}_{20} = $$

$$= \begin{bmatrix} -sin(\,wt_2 + \theta_{off}\,)cos\,\phi_2 \\ cos(\,wt_2 + \theta_{off}\,)cos\,\phi_2 \\ sin\,\phi_2 \end{bmatrix} \quad (5)$$

We can see that in Eq. (1) there are 3 unknown parameters. Since to every transmitter, we can get only two equations, at least two transmitters are needed to realize coordinate solve.

4. Adjustment calibration

Beam adjustment method based on collinearity condition equations is an important analytical method in close-range photogrammetry. Since it is rigorous in data processing and applicable in the conditions where require a high precision solver but lack of controlled conditions, it is the most effective way to establish a global control network [5]. In wMPS system, beam adjustment calibration is used to find out the position relationship among transmitters, we call this process system setup. Fig. 6 shows the principle of setup.

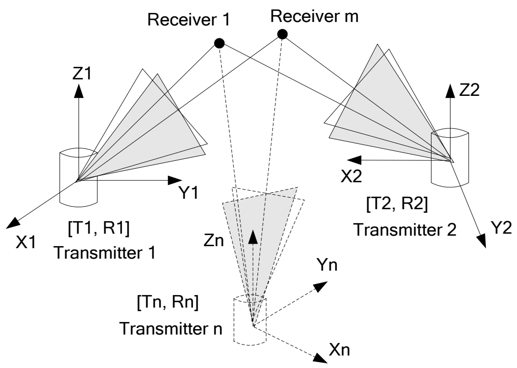

Fig. 6 Schematic diagram of system setup

However some work need to be done in advance:

1. Obtaining of inner parameters: Inner parameters actually refer to the relative position of laser planes in local coordinate system at initial moment.

2. Estimation of initial value: Initial value refers to the estimation of the local coordinate system. Auxiliary equipment (such as laser trackers) is used to establish a global coordinate system, according to the above defination of the local coordinate system.

3. Layout of control points: Control points are used to create collinear condition equations in network. One principle should be obeyed to guarantee the setup quality is that the control points should be arranged in the the area to be measured.

$\begin{bmatrix} T_i & R_i \end{bmatrix}$ is the transformation matrix of each transmitter. Supposing that the network is composed by *n* transmitters and *m* receivers are arranged in space to work as control points. Taking Eq. (1) as setup constraint equations, the number of nonlinear equations is $2nm$, and the number of unknown parameters is $(6n+3m)$ in all. If the numbers of transmitters and control points meet the condition that

$$6n + 3m < 2mn \quad (6)$$

Then we can get the transformation matrix for each transmitter by beam adjustment algorithm [6]. After that, system scale will be obtained through defining a standard distance and comparing it with the measuring result of wMPS. Adjustment calibration method executes a nonlinear optimization on the basis of system constraints without known control point's coordinates, which has fewer error elements and high precision [7, 8].

5. Experiment

A practical network measurement system was constructed with three transmitters to verify the system performance. The three transmitters were placed into a triangle, but not a line. The distances between the stations besides and middle were about 2 m. And two receivers were installed on both ends of the ceramic standard scale stick, the length of which had been calibrated before using an optical image instrument, labeled as 562.367 mm. As Fig. 7 shown are the transmitters and receivers, as well as the ceramic standard scale stick.

Fig. 7 Transmitters and receivers used in experiment

First, we took a test of the stability of time measurement of all the three transmitters and transformed the time value into corresponding angles according to the rotation period of each transmitter. Then, adjustment method depicted above was used to implement setup.

After that we placed the ceramic standard scale stick with two receivers at both the end about 10 m away from the transmitters. The result of distance error measurement is listed in the Table. Together there were 10 locations picked to do the experiment. Each distance we got had a comparison with the standard value 562.367 mm.

Table

Distance error measurement result

Location index	1	2	3	4	5	6	7	8	9	10
Measured value, mm	562.371	562.284	562.324	562.318	562.334	562.392	562.342	562.395	562.424	562.469
Distance difference, mm	0.004	-0.083	-0.043	-0.049	-0.033	0.025	-0.025	0.028	0.057	0.102

6. Discussion

As to the stability testing at the beginning, we found out that it took some time to achieve the status of stability. We suspect that it has something to do with the transmitter's mechanical structure and the smoothness of the encoder. From the result of stability of angle measurement we can see that after it achieves a steady status, the stability of angle measurement will be $\pm 2''$, which means the distance error at the range of 10 m will be 0.094 mm. It is in accord with the distance error in the second experiment.

In the distance error test, since the measurement network was established by three transmitters, it would have stronger coplanar constraints than the network with two transmitters. The set-up process and the relative location of stations and regions to be measured are usually taken into consideration on the job site. The result of distance error measurement indicated that in a range of 10 m, the overall precision could reach 0.1 mm. Moreover, we can measure any position without losing accuracy by adding transmitters in suitable place around the area.

Any way, there is still a lot of work to do with this new system. The error patterns and factors should to be clear and certain. And then the method used to reduce the error so as to improve the precision should be studied.

7. Conclusions

In the initial study of wMPS, we have established its mathematical measurement model, explored the setup algorithm and built a double-decker architecture, including task-level and management-level. For further study, shaft stability of transmitters should be improved; a mathematical model for error analysis should be established and all the relative error sources such as setup and system arrangement need to be analyzed systematically. In addition, system software is also an important part to make this system more powerful [9].

wMPS makes up for the deficiencies that exist in theodolite and laser tracking systems in industrial applications. It is competent for real-time monitoring of key points, on line navigation of work fixture, real-time guidance of assembly and so on. The experimental results show that the overall accuracy of the system can be achieved within 0.1 mm at the range of 10 m which reaches the level of iGPS. It can be predicted that wMPS will have a broad application in modern digital manufacturing for its advanced principle and unique advantages.

Acknowledgements

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DARBO ZONOS MATAVIMO IR POZICIONAVIMO SISTEMA SU SUKAMOMIS LAZERIO PLOKŠTUMOMIS

R e z i u m ė

Straipsnyje supažindinama su nauja didelių matavimo ribų koordinatinio matavimo sistema pavadinta darbo zonos matavimo ir pozicionavimo sistema, naudojanti skanuojančio lazerio plokščius spindulius ir daugiakryptį pozicionavimą. Naudojant šią sistemą galima tiksliai matuoti didelėse ribose. Pateikiama matavimo ir pozicionavimo sistemos struktūra ir sukurtas daugiaplanių ryšių matematinis modelis pozicionavimui globalioje koordinačių sistemoje. Aprašytas kalibravimo metodas ir derinimo procesas. Sukurta patikima trijų keitiklių matavimo schema. Eksperimento rezultatai parodė, kad bendra sistemos paklaida yra pakankami stabili ir nedidesnė nei 0.1 mm 10 m matavimo intervale.

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WORKSPACE MEASURING AND POSITIONING SYSTEM BASED ON ROTATING LASER PLANES

S u m m a r y

This paper introduces a novle type of large-scale coordinate measurement system by the name of wMPS (workspace Measurement and Positioning System), which is based on scanning planar laser beams and multiderection positioning. wMPS provides a novel technical solution for large-scale coordinate precision measurement. System configuration of wMPS was represented and multiplane constraint mathematical model was established in global coordinate system to achieve positioning. Adjustment calibration method as the basis for measuring was described, as well as the setup process. At last, an actual measuring network using three transmitters was built up. The experiment results show that the overall accuracy of the system can be achieved within 0.1 mm at the range of 10 m and has a satisfactory stability.

Keywords: workspace measuring and positioning system, rotating laser planes.

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