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Architectural stability analysis of the rotary-laser scanning technique

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ABSTRACT

The rotary-laser scanning technique is an important method in scale measurements due to its high accuracy and large measurement range. This paper first introduces a newly designed measurement station which is able to provide two-dimensional measurement information including the azimuth and elevation by using the rotary-laser scanning technique, then presents the architectural stability analysis of this technique by detailed theoretical derivations. Based on the designed station, a validation using both experiment and simulation is presented in order to verify the analytic conclusion. The results show that the architectural stability of the rotary-laser scanning technique is only affected by the two scanning angles' difference. And the difference which brings the best architectural stability can be calculated by using pre-calibrated parameters of the two laser planes. This research gives us an insight into the rotary-laser scanning technique. Moreover, the measurement accuracy of the rotary-laser scanning technique can be further improved based on the results of the study.

1. Introduction

For geometric and positioning information monitoring and measurement in large-scale aircraft docking, shipbuilding and manufacturing, the rotary-laser scanning technology is a useful and an indispensable measurement technique for the good performance of lasers including the wavelength stabilization, strong coherence and well directional property [1–4]. Lots of experts develop such scanners using similar principles. Lopez et al. have developed scanners based on the novel method of precise measurement of plane spatial angles applying to geometrical monitoring to predict their structural health during their lifetime [5]. Básaca-Preciado et al. designed an optical 3D laser measurement system for navigation of autonomous mobile robot, which is capable of performing obstacle avoiding task on an unknown environment [6]. Rodríguez-Quiñonez et al. presented a 3D medical laser scanner based on the novel principle of dynamic triangulation, and they analyzed the method of operation, medical applications, orthopedically diseases as Scoliosis and the most common types of skin to employ the system the most proper way [7]. Guan et al. use mobile laser scanning data for automated extraction of road markings and develop relevant algorithms [8]. Lots of other experts also make achievements in this area, which are unable to detail here [9–17].

The rotary-laser scanning technique of this kind can provide very good performance like high accuracy, large measurement range, high usability and high efficiency, which extremely meet the demand of measurement applications at the scale of tens of meters [18–22].

A single station based on the rotary-laser scanning technique is designed and presented in this paper. As an important component of a large-scale 3D measurement network, the single station's characteristic determines the performance of the whole network. So, precisely mastering the characteristic of this rotary-laser scanning technique is an important work both in theory and practice.

In recent years, some researchers have done a lot of work on studying the characteristic of a single station based on the rotary-laser scanning technique. For instance: Muelaner demonstrated how the angular uncertainties can be determined for a rotary-laser automatic theodolite of the type used in (indoor-GPS) iGPS networks [23]; Xiong used the similar method as Muelaner to find the angle-measuring ability of a single transmitter of the (workspace Measuring and Positioning System) wMPS [24,25], and so on. However, the above work just focused on the accuracy of the observed angles by testing procedures, not profoundly analyzed the construction feature of this technique using a pure and rigorous mathematical derivation, nor did they give precise instructions on how to utilize the feature to get the best performance in practical applications. In this paper, a rigorous perturbation

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analysis on the matrix equation abstracted from the rotary-laser scanning technique is first presented which gives a geometrically concise result, then, Monte Carlo simulations combined with some experimental results are illustrated which are used to verify the theoretical conclusion. As an instructive result, we find that the architectural stability remains the same in the circle direction around the single station, whereas it changes a lot with the change of the elevation angle. Moreover, the elevation is directly determined by the two scanning angles' difference, which is gotten from the two laser fans' continuously strikes on the receiver (the photoelectric sensor used to receive the laser signal). So, we have that the volume with the optimum architectural stability around the station can be obtained by detecting the difference of the two scanning angles. If it meets the value which is calculated using the pre-calibrated parameters of the laser planes, we get the optimum measurement volume. Obviously, using the volume with the optimum stability to implement some monitoring or measurement work is the best solution we should choose. Furthermore, our analysis reveals the internal architecture of the rotary-laser scanning technique. A good understanding on the internal architecture will be helpful in tapping the accuracy potential of this technique in the large-scale measurement networks.

We divide this paper into the following sections: Section 2 describes the measurement model of the rotary-laser scanning station and demonstrates the characteristic of the station from a rigorous mathematical point of view. Section 3 designs the validation procedures whose results noticeably meet our derived result. In Section 4, we present concluding remarks and a brief overview of future improvements.

2. Measurement model of the station based on rotary-laser scanning technique

2.1. General introduction of the station

The station can be treated as a spatial angle measurement system. The components of the system and construction of the station are shown in Fig. 1.

As illustrated in Fig. 1, the rotary-laser station consists of a rotating head and a stationary base. Two line laser modules are fixed on the rotating head, which can emit planar laser beams with different tilt angles. Several pulsed lasers are mounted around the stationary base. With the rotating head spinning at a predefined speed in anti-clockwise direction, the station generates three optical signals: two nonparallel planar laser fans rotating with the head of the station and a cyclical omnidirectional laser strobe emitted by the pulsed lasers synchronously every time the head rotates to the predefined position of every cycle. The pulsed laser works at the frequency around 2000 r/min. This is a working frequency not requiring much on the rotor structure.

The photoelectric receiver captures the three optical signals and then converts them into electrical signals through a photoelectrical sensor. The signal processor is used to binarize the electrical signals into logic pulses, differentiate the logic pulses and record the time information of the laser planes.

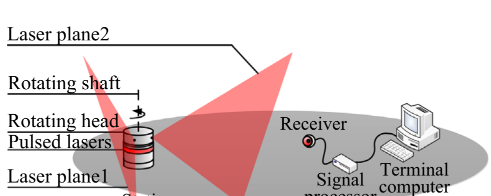

Fig. 1. Spatial angle measurement system.

As shown in Fig. 2(a), the initial time is defined as the time when the head of station rotates to a predefined position (initial position) and the pulsed lasers emit the synchronous laser strobe. At the initial time, the receiver captures the synchronous laser strobe and records the time as t_0. Rotating with the head, the two laser planes scan the measurement space around the station. As shown in Fig. 2(b), when laser plane 1 sweeps past the receiver, the time is recorded as t_1. Assuming that the angular velocity of the rotating head is ω, then the scanning angle θ_1 of laser plane 1 from the initial position to the position where it passes through the receiver can be obtained:

$$\theta_1 = \omega(t_1 - t_0) \tag{1}$$

In a similar way, to laser plane 2:

$$\theta_2 = \omega(t_2 - t_0) \tag{2}$$

For the problem that the laser plane's thickness becomes wider as it travels longer, like a cone which may deteriorate the measurement accuracy, we give explanations as follows:

This is a phenomenon that exists objectively. It can deteriorate the measurement accuracy especially at a distance around 10 m. At present, we resolve this problem through two methods. One is to select a laser with good parameters which has less than 3 mm width at 10 m distance, the other is to detect the energy center of the spot at the receiver using some method like in references [26,27]. However, what we want to say is that the topic we talk about in this paper is the architectural stability of the laser scanning technique we introduced above. The slight cone-like property of lasers affects the measurement accuracy, but not significantly affects the architectural stability as the 3 mm width at 10 m has not much impact on our topic. So, in this paper, we assume that the laser performs ideally as a plane.

2.2. The construction of the line equation

Before going any further, we define the coordinate frame of the station. The z-axis is the rotation axis. Origin is the intersection of the rotation axis and laser plane 1 at the initial position. The x-axis through the origin is on plane 1 and perpendicular to z-axis. The y-axis is determined according to the right-hand rule, see Fig. 3. Therefore, the rotary-laser station can be treated as two nonparallel half-planes rotating around axis Z and an omnidirectional pointolite emitting laser pulse train with a fixed-frequency at the origin O.

As described in Section 2.1, we can obtain the scanning angles of the rotary-laser planes using a single station and a receiver (P_i). Benefiting from the tilted structure of the two line laser models, we can obtain the elevation information as illustrated in Fig. 3(b). To better explain the elevation measurement principle from the slope of the two laser planes, we mathematically describe the two

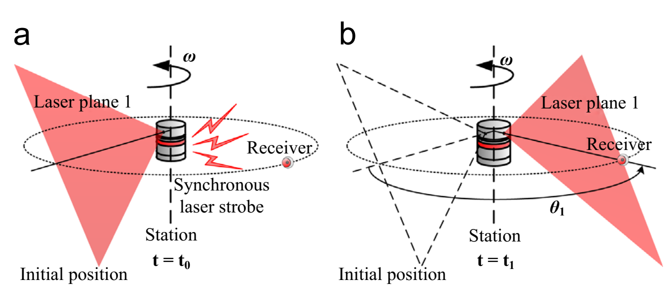

Fig. 2. Schematic of the scanning angle measurement: (a) the initial time and (b) the time when laser plane 1 sweeps past the receiver.