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Volumetric performance evaluation of a laser scanner based on geometric error model

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ABSTRACT

We discuss a geometric error model for those large volume laser scanners that have the laser source and a spinning prism mirror mounted on a platform that can rotate about the vertical axis. We describe the terms that constitute the model, address their effect on measured range and angles, and discuss the sensitivity of different two-face and volumetric length tests to each term in the model. We report on experiments performed using commercially available contrast targets to assess the validity of the proposed model. Geometric error models are important not only in improving the accuracy of laser scanners, but also in facilitating the identification of test procedures for performance evaluation of these instruments and therefore in the development of documentary Standards. The work described in this paper lays the foundation for such efforts.

1. Introduction

Large volume laser scanners are used for a variety of purposes including dimensional metrology of large artifacts, digitization and reverse engineering, historical preservation and archiving, etc. The extremely high data collection rates and noncontact measurements made possible through advancements in optoelectronics are rapidly shifting dimensional metrology toward this form of measurement. There are currently two broad mechanical designs of large volume laser scanners suitable for dimensional metrology. One design is similar in construction to a laser tracker, where the laser source is stationary and located in the base and the spinning mirror is mounted on the gimbal head. Such a design has already been discussed in the literature [1] and is not the focus of this paper.

In this paper, we present a geometric error model for the second design, which comprises those laser scanners that incorporate a source and a spinning mirror on a platform that can rotate about the vertical axis. We describe the terms in the model and their influence on the measured range and angles. The model parameters apply to front-face measurements of the scanner (vertical angle in the range of 0°–180°) but some scanners, such as the one tested, also allow measurements in back face. That is, the target can be measured by rotating the scanner 180° about the vertical axis (i.e., the horizontal angle changes by 180°) and then rotating the mirror past 180° in the vertical angle to locate the target. We describe how corrections to the measured range and angles can be obtained for measurements made using both faces of the scanner. The model applies to all scanners that employ such a stacked construction and is not limited by the technology employed to detect range. The particular scanner considered in this study is a phase shift scanner that uses amplitude modulation to detect range [2].

The objective of this work is not simply to model errors for the purpose of reducing or eliminating their effects, but also to understand how these errors manifest as two-face or point-to-point length errors so that we may then identify suitable artifact test positions and orientations for the performance evaluation of these instruments. We therefore discuss possible placement of targets and reference lengths to achieve high sensitivity to the different terms in the model. We report on experiments performed using

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commercially available contrast targets to assess the validity of the proposed model.

Laser scanner measurements suffer from several other error sources such as those associated with the optical interaction of the laser and the part surface, the choice of targets, material properties, surface finish, reflectivity, etc. Determining the optimal positioning of targets and reference lengths to detect opto-mechanical scanner errors will comprise one test among a suite of performance tests for laser scanners. In this paper we only focus on the opto-mechanical errors of scanner performance evaluation and use target materials that minimize the interaction of the scanner beam with the target properties.

It should be pointed out that most commercial laser scanner systems *do* incorporate a geometric error model within the system but that information is often proprietary. Further, scanner manufacturers may not necessarily provide the user with the ability to determine the parameters of the model (a procedure referred to as 'compensation') in situ in a manner similar to that of laser trackers. This is possibly because laser scanner systems available today have less stringent accuracy specifications due to ranging errors that are substantially larger than errors induced by optical and geometric misalignments within the system. However, ranging accuracies of laser scanners have been improving steadily over the years and it will only be a matter of time before ranging errors are substantially smaller and scanner compensation will become an important aspect in performing accurate measurements. As in the case of laser trackers, ranging performance evaluation of a laser scanner along the radial direction can be done independently of volumetric performance evaluation. The focus of this paper is on evaluating the volumetric performance, not ranging.

Much of the focus of reported research [3–6] in the literature on scanner modeling is on the subject of self-calibration, that is, the development of procedures to mitigate the effects of geometric misalignments. The work described in this paper not only details the geometric misalignments within the system, but more importantly, suggests placement of targets and reference lengths in order to expose the presence of such errors, thus facilitating the creation of documentary (national or international) Standards for performance evaluation in the future.

2. Coordinate system and terminology

First we define the coordinate system associated with a perfect laser scanner. In later sections we will address the geometric errors in the scanner. Consider a Cartesian coordinate system *XYZ* that is fixed to the scanner base with its origin located at *O* as shown in Fig. 1. The *Z* axis is referred to as the vertical axis or the standing axis and the *XY* plane is referred to as the horizontal plane. We define the *Z* axis to be coincident with the vertical rotation axis of the scanner. The mirror rotation axis is referred to as the horizontal axis, also known as the transit axis. Two axes *OT* and *ON* are attached to the platform which rotates about the *Z* axis. Axis *OT* is defined to be coincident with the horizontal axis of a perfect scanner and is defined to be in the *XY* plane. Point *O* is also the point where the laser strikes the mirror (for a perfect scanner) and is reflected toward the target *P*. Axis *ON* is normal to *OT* and also lies on the *XY* plane and is oriented such that *ON, OT*, and *OZ* form a right handed coordinate system. Point *O′* lies on the *OT* axis and is the source where the laser is emitted. After reflection off the mirror the laser beam path lies in the *ONZ* plane, this also defines the normal to the mirror surface to be tilted at a 45° angle with respect to axis *O′T*. We refer to the plane *O′OP* as the laser plane; this plane contains the laser beam emitted from the source and the beam reflected to the target *P*. Axes *O′N′* and *O′Z′* intersect at point *O′* and are parallel to *ON* and *OZ*, respectively.

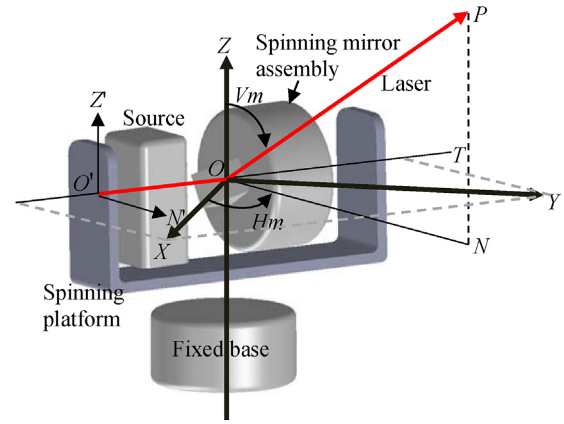

Fig. 1. Coordinate system definition for a perfect scanner.

We adopt the following terminology. The measured range, horizontal angle, and vertical angle are denoted by *Rm*, *Hm*, and *Vm* respectively. The corrected range and angles are denoted by *Rc*, *Hc*, and *Vc* respectively. The corrections to the range and angles are denoted by ΔRm, ΔHm, and ΔVm. For the purposes of computing errors associated with geometric misalignments in the scanner, the corrected values are also assumed to be the true values; we do not consider random errors in this paper. The corrections are added to the measured values to obtain a better estimate of the corresponding quantities. The corrections have the opposite sign than their associated error and hence the corrections are the differences between the true values and the measured values.

The directions for the positive (increasing) horizontal and vertical angles are shown in Fig. 1. The horizontal angle *Hm* is the extent of the angular rotation of the spinning platform about the vertical axis. The Vertical angle *Vm* is the extent of rotation of the spinning mirror about the horizontal axis. While the pole (+*Z* axis) is the zero for vertical angle measurements, there is no absolute zero for horizontal angle measurements for the scanner that we tested. The spinning platform can be positioned at any orientation and set as the zero.

3. Model parameters

There are several sources of offsets, tilts, and eccentricities in the opto-mechanical construction of the laser scanner that may produce errors in the measured coordinates. We describe them in this section; a list is provided in Table 1. The equations presented in this paper are simply stated but can be derived using simple trigonometry. They are valid to first order in *x*/*R*, where *x* is the offset and *R* is the range value, over the entire measurement volume except for the points near the poles, i.e., $Vm = 0°$ and $Vm = 180°$. The $Vm = 180°$ case is unimportant since the scanner tripod blocks this region from being measured. The region near the pole (e.g., within 1°) where $Vm = 0°$ is more complicated. In particular, several of the error correction terms have singularities at the poles. Additionally, some error sources such as mirror offset (Section 3.3) prevent the scanner from physically directing the laser beam in the pole (i.e., *Z*) direction even though the scanner will report measured values with $Vm = 0°$. Consequently, it is recommended that measurement data with *Vm* near zero be rejected because the uncorrected data is unreliable and the corrections are not applicable. A more complex model that accounts for these effects will be addressed in another publication.