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Design and analysis of a 3D laser scanner

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ABSTRACT

A new laser scanner is designed, built and its scan measurement uncertainty is analyzed and deviations are minimized. The design is comprised of the physical setup of scanner, point cloud extraction as well as procedures for scanner calibration. It is designed to operate in a spherical domain, thereby giving wide imaging view possibilities. By exploiting strategies in real-time serial communication and image processing, the prototype acquires uniformly dense point cloud from a geometric specimen. In addition to design, rather than using benchmark geometry to only assess the accuracy of the scanner, data obtained from a known geometric model are used to modify the scanner parameters to obtain optimal results. A method of finding scanner parameters that provides least point deviations is developed using least squares. The methods of calibration and optimization of the scanner prototype in this paper can be extended to any type of scanner design.

1. Introduction

The reason why conventional coordinate measurement machines (CMM) have been widely utilized as a standard measurement device for over 40 years is due to their high precision contact sensors that satisfy industrial standard [1]. Beyond their accuracy, CMM can be expensive and slow. The low speed is due to the fact that data acquisition is carried out point-wise as the probe is displaced continuously. It does not support fast and efficient instantaneous linear or 2D data acquisition prevalent in image sensors. Moreover, probe-type measurement devices are incompatible with flexible or deformable parts and reaching some points in complex geometry can be challenging. Therefore, there is benefit in exploring possibilities in non-contact multi-points acquisition based scanners for geometric reconstruction.

In light of contact-type CMM drawbacks, non-contact measurement devices have gained some interest in recent years and have taken an integral part in various industrial applications. Several commercial products—referred to as 3D scanners or digitizers—have also emerged. Most of the scanners use led-based projectors or lasers as illumination source. As outlined by Molleda et al. [2], led projectors provide more uniform illumination and sharper edges. However, due to size and cost constraints, a class of non-contact scanners that uses laser as a source of light to project known pattern on geometry is of particular interest in this work. In addition to illumination, an important feature of scanners is image sensing. The popular camera sensor types are complementary metal oxide semiconductor (CMOS) and coupled-charge device (CCD). Based on size, functionality, performance and cost, CMOS is preferable in most machine vision applications [1]. The choice of camera resolution is made based on computation capacity and speed requirement.

Theoretically, by optical diffraction limitation imposed by Rayleigh's criterion, the scanner camera used should be able to resolve distances greater than about 3 μm taking a typical lens f-number as 4 [2]. However, the actual accuracy of triangulation laser scanner can hardly reach around 30 μm even in a controlled environment [3]. Systematic errors arising from laser source, reflection surface, lens defects and environmental non-uniform illumination are the cause of increased uncertainty. In addition, image sensor noise adds error to measurements and partially occluded width of the light beam will give wrong data at some regions.

Studies on estimation of uncertainty in laser reconstructions of geometric part have helped shed some light on how the magnitude of error is implicitly related to the part geometry. Isheil [4] found that angle between laser plane and camera axis β, significantly affects local error of measured part. Angles exceeding 40° for regions around 100 mm from camera were observed to contribute systematic error higher than 15 μm. The random error is also found to have magnitude reaching 30 μm. By geometric intuition, Curless and Levoy [5] provided instances where positions of sensor, surface and illuminant could result in erroneous measurement. Occlusion and discontinuities in reflectance or shape were mentioned as sources of errors. Laser scanners extract stripes resulting from the intersections of central plane of incident laser line beam with

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the scan object. The laser line beam is not a perfect plane because it has width of about 0.5mm to 1mm depending on the imaging sensor. It becomes critical to quantify the form error that arises from the surface form of a measured object. Zhou [6] derived an expression that estimates form error originating from deviation of reflected stripe beam center and the original central incident plane for a Lambertian reflection with relatively very small lens radius. Uncertainty approaching magnitudes of 15 μm were ascribed to the mentioned form errors. The form dependence of laser structured light scanners has made standardization rather difficult. In most cases, a known geometric model is used as measurement benchmark of such scanners. In the designed laser scanner of this paper, the benchmark geometry is used for not only validation of scan results but also to reduce positional and systematic errors. In general, the global error in commercial 3D laser scanners has been analyzed in details in literature [3,4,7], they generally possess errors ranging from 40 to 300 μm. Their uncertainties are usually about one order more than contact type scanners [8], which is why probe-type CMMs are still predominantly in use.

2. Mechanical design

The scanner in this study is designed based on requirements of high precision and wide scan coverage of part by allowing multiple camera view angles. Therefore, a prototype that allows sufficient relative displacement between camera and workpiece is sought. Feasibility and stiffness of supporting component are also considered in the design. As depicted in Fig. 1, a design that allows camera view direction that covers a form of hemispherical dome was designed and tested. The overall measurement depends directly on the repeatability of step positions in spinning and lifting as well as uncertainty in critical scanner geometric dimensions. Hence, these issues are studied and remedies are proposed in subsequent sections.

All components were carefully selected and deformations of critical components are checked to ensure that displacement uncertainty is reduced. The lift frame, which supports the camera and lasers, is particularly significant since it must not transfer a critical torque the motor cannot handle. For this reason, it is fabri-

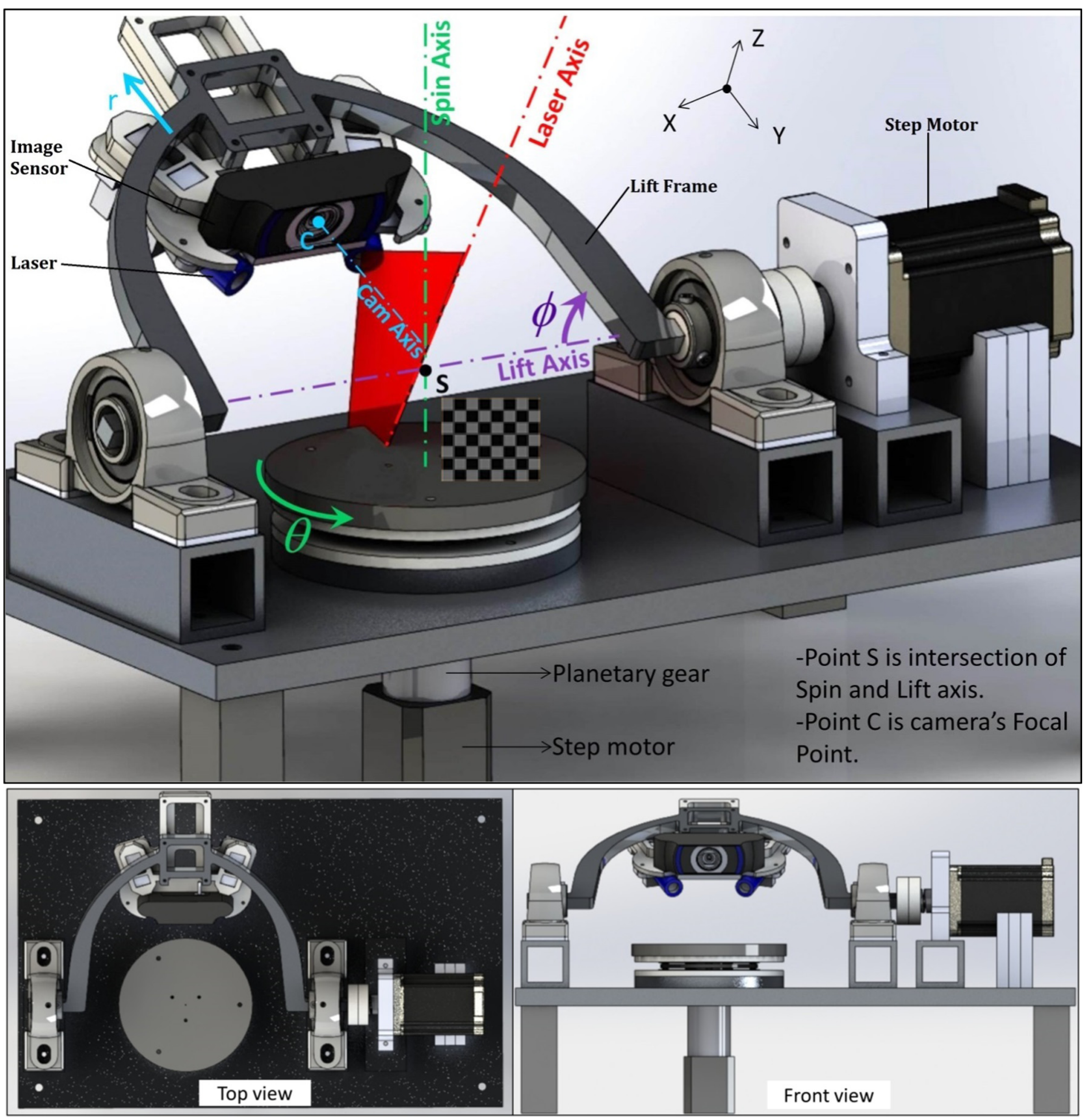

Fig. 1. Scanner setup showing relevant geometric axes, calibration grid and other design features with front and top views.