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Development and calibration of an integrated 3D scanning system for high-accuracy large-scale metrology

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ABSTRACT

Quality control in advanced manufacturing requires automated and high-accuracy large-scale 3D measurement. This paper proposes a high-accuracy, low-cost 3D scanning system by integrating industrial robot with precise linear rail and laser sensor. The measuring principle and system construction of the integrated system are introduced in detail. A mathematical model is established for mapping the change of the laser sensor frame while it scans along the linear rail and a sphere-based algorithm for rail orientation calibration is introduced. Subsequently, taking the robot positioning error into consideration, an enhanced hand–eye calibration method is proposed to determine the relationship between robot end-effector and rail scanning frame. Validation experiments were performed, a maximum distance error of 0.071 mm was detected within the rail range and a mean/maximum distance error of 0.309/0.604 mm was detected in the robot volume. A large-scale scanning instance also shows that integrated robotic scanning system features high-efficiency and high-accuracy.

1. Introduction

Large castings and welding constructions are considerable resources for modern advanced manufacturing, especially in automobile, shipbuilding and aerospace industries. Automated and accurate three-dimensional (3D) shape measurement of these large-scale components is of great significance not only in product quality control but also in minimizing time/manpower consumption. Meanwhile, accuracy specification of the key local features on these large parts and components, such as characteristic ridges and assemble holes, will have direct impact on the assembly quality and reliability of the products. So it is desirable that the large-scale 3D scanning system could also perform high-accurate positional measurement of these local features. Furthermore, given the complexity and interference of the industrial field environment, robustness of the measurement system is also preferred for the large-scale 3D shape and positional measurement.

Tremendous efforts have been devoted to the field of large-scale 3D shape measurement and a wide range of apparatuses have been developed [1]. Leica T-Scan is a high-speed hand-hold scanner normally used for large-volume 3D modeling [2]. But its high cost and the characteristic of demanding manual operation have limited its widespread application. With the development and progress in optics, image processing and computer vision techniques, high-accurate and high-throughput visual sensors have been integrated with the conventional coordinate measuring machines (CMMs), which are frequently used in contact measurement, to acquire the 3D shape information of dies, molds and gear boxes [3–5]. However, this method has a drawback that only a tiny percentage of products in the assembly line could be sampled and brought to the CMM for inspection due to its limited

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measurement efficiency. Furthermore, CMM is often not robust enough for online inspection in the industrial field environment. In recent years, the manufacture precision of industrial robot has been improved significantly while cost reduced continuously, robotic technologies (off-line programming and simulation tools) have been developed rapidly, all of these have made the robot become an economical and flexible orienting device, compact and portable visual sensors are increasingly integrated to the robotic measurement system [6,7]. Further, Larsson and Li have both introduced a turntable surrounding the robot to extend the measuring range of the robotic system [8,9]. This method is promising because it combines the industrial robot's flexibility and visual sensor's accuracy. And it has been applied extensively for geometry reverse engineering (GRE) and flexible automated on-line inspection of parts in sectors such as automotive assembly line. Another popular technology for large-scale scanning application, fringe projection technique, has been well developed and widely used for its high-resolution and whole-field reconstruction of the surfaces at video frame rates. The methodology based on integration of industrial robot with fringe projection sensor has been applied for precise large-scale surface defect inspection and accurate surface digitization, such as the large hull yacht [10,11]. But in measuring principle, the fringe projection sensor is usually not capable of detecting the edge of features at subpixel accuracy, so it is difficult to ensure high accuracy when measuring diameter of assemble hole or position of characteristic ridge.

Nonetheless, measuring accuracy of these robotic measurement systems is limited by the robot positioning accuracy. Although industrial robots generally have high repeatability, their accuracy is much worse [12,13]. Scanning with all-angle robot arm will always exhibit ripple, which makes high-accuracy measurement of local features difficult to achieve. On the other hand, in order to reconstruct the measured object in the global reference frame, one has to calibrate the relationship between the laser sensor and robot end-effector, which is also referred as hand–eye calibration. Different methods for hand–eye calibration have been reported in extensive literature, the most typical method is to solve the homogeneous equation $AX = XB$ or $AX = YB$ where X and Y are the unknown hand–eye transformation and the robot-world transformation, A and B are the movement of robot end-effector and camera. Several parameter identification methods including linear solution [14,15] and nonlinear solution [16,17] were reported. Li proposed a new nonlinear approach for calibrating the transformation between the off-the-shelf visual sensor and the robot end-effector by using a standard sphere [18,19], in which a standard sphere is designed as the calibration target and the sphere center is referred to the fixed reference point. Translational and rotational motions of the robot are made successively, and the visual sensor measures the sphere center in different robot poses, orientation and position of the laser sensor frame are calibrated in two steps. This method is easy to implement, but errors in the first step, orientation calibration, will transform to the next position calibration process. Moreover, robot movement is involved in the hand–eye calibration process, but robot positioning error is not considered, so it is difficult to guarantee the accuracy of hand–eye calibration.

In this paper, a novel integrated robotic scanning system is developed for high-accuracy large-scale measurement. In consideration of the limited measuring range of the laser scanner, a precise linear rail is introduced to the traditional robot-laser sensor system (with only a laser sensor mounted on the robot end-flange). A line structured laser sensor is mounted on a precise linear rail and the combination of the laser sensor and the linear rail can be referred as an area scanning system, which is re-named as LRSs (Linear Rail Scanning system) in this paper. With the LRSs, shape and positional information of the local features within the rail range could be obtained in a high degree of precision because no robot positioning error will be introduced. And taking the robot as orienting device, large-scale scanning can be achieved efficiently. This integrated system, consisting of off-the-shelf components, combines the flexibility of the industrial robot and the high precision of the laser sensor and linear rail. On the other hand, in order to improve the measuring accuracy in the large-scale volume, an enhanced sphere-based method is proposed for accurate and efficient calibration of the integrated 3D scanning system, avoiding external measurement device. The moving direction of the linear rail is calibrated first to formulate the changing of the laser sensor frame while it scans along the linear rail. And an initial value for hand–eye relationship is determined with an improved sphere-based method, which could estimate the orientation and position in one step. Then an enhanced hand–eye calibration method is proposed to estimate the errors in initial hand–eye transformation, with consideration of the robot positioning error. A mathematical model is established to formulate the relationship among sphere centers measured in different robot poses, robot positioning error and hand–eye transformation error. By changing the position of the standard sphere in the robot workspace, the robot would get adequate motion in its workspace, robot kinematic parameter errors and hand–eye transformation errors are estimated at the same time. Verification experiments show that the presented approach has improved the accuracy of the robotic 3D scanning system significantly. The integration of these components cannot only perform accurate and comprehensive large-scale 3D shape and positional measurement, but also significantly promote efficiency and save cost.

The rest of the paper is organized as follows. Section 2 introduces the measurement principle and the construction of the integrated 3D scanning system. Calibration method for the precise linear rail moving direction is presented in Section 3 and the enhanced hand–eye calibration method is detailed in Section 4. Calibration procedure of the integrated scanning system is presented in Section 5. Also in Section 5, measuring accuracy of the system is evaluated in the rail travel range as well as in the robot volume, and a large-scale scanning instance is presented too. The paper will finish in Section 6 with a short conclusion.