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A practical coordinate unification method for integrated tactile–optical measuring system

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ABSTRACT

To meet the requirement of both high speed and high accuracy 3D measurements for dimensional metrology, multi-sensor measuring systems have been developed to measure, analyse and reverse engineer the geometry of objects. This paper presents a new development in coordinate unification called the “centroid of spherical centres” method, which can be used instead of the traditional method which uses three datum-points to perform the geometric transformation and unification of tactile and optical sensors. The benefits of the proposed method are improved accuracy in coordinate unification and the method is used to integrate a coordinate measuring machine (CMM) and optical sensors (structured light scanning system and FaroArm laser line probe). A sphere-plate artefact is developed for data fusion of the multi-sensor system and experimental results validate the accuracy and effectiveness of this method.

1. Introduction

Applications of hybrid system in dimensional metrology are of increasing importance in quality control, reverse engineering (RE) and many other industrial fields. The existing CMM methods [1] are widely used for industrial dimensional metrology, but the digitisation process is very time-consuming for the acquisition of the first set of points on complex, freeform surfaces. An alternative approach is represented by non-contact digitisation of surfaces based on optical techniques, such as time-of-flight [2], computed tomography [3], laser scanning [4–6], stereovision [7] and structured light [8–10]. These optical instruments can efficiently capture dense point clouds in terms of speed and reduces the human labour required. However it is usually difficult for the optical sensors to digitise the non-surface objects, such as slots or holes, due to occlusions and obscuration of these artefacts.

Even though tactile and optical sensing technologies are widely used in data acquisition in dimensional metrology, it has been shown that each technique has its own characteristics and limitations, which lend them to particular applications. While fusing data sets, characteristics such as resolution and measuring ranges have to be considered. On the other hand, due to the different measuring techniques and their physical working principles, different interactions between the workpiece and sensor occur and different surfaces are captured [11]. The reduction of the lead time in RE, and the increased requirements in terms of flexibility as well as accuracy have resulted in a great deal of research effort aimed at developing and implementing combined systems based on cooperative integration of in-homogeneous sensors such as mechanical probes and optical systems [12–17].

However, a limitation of the prosed systems is that the integration of the optical system with the CMM generally takes place but is limited at the physical level, flexibility level and usability level. In most commercial multi-sensor systems, a tactile sensor (such as stylus) and optical sensor (such as laser scanner) share the same probe fixed on the CMM arm and recalibration is needed after each change of sensor. Bradley and Chan [14] and Zexiao et al. [15] each present a complementary sensor approach for RE; a touch probe and a laser sensor are attached to CMM *z*-axis arm and two sensors coordinate system can be referenced to the same one by measuring the same high precision ball bearing. A hybrid contact–optical coordinate measuring system is designed by Sladek et al. [16], but the specific unification algorithm is not given. Yunbao Huanga et al. [18] proposed an iterative registration and fusion method for multi-sensor calibration, it uses iterative closest point (ICP) algorithm [19] to achieve surface fusion and Kalman filter [20] to obtain accurate surface registration. However ICP method and its variants [21,22] are more suitable for registration of data sets measured by the same or homogenous sensors (for example structured light and laser) which have similar resolution and accuracy; it also requires a sufficient number of coincident points from different data set to obtain better registration accuracy.

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This paper describes a flexible and effective approach for the integration of CMM with structured light system and CMM with FaroArm laser line probe to perform 3D inspections or reverse engineering of complex and freeform surfaces. A sphere-plate artefact is developed for unification of the hybrid system and it does not need the physical integration of optical sensors onto the CMM ram, but includes their combination at the measurement information level. This sphere-plate uses nine spheres rather than a traditional plate with three spheres to perform the geometric transformation. The system unification is achieved by measuring the spheres calibration board and then the measurement results from all of the optical sensors and the CMM probe head are combined into one set. This operation has to be done prior to any measurements, after the calibration of separate systems. It is carried out only once before a series of measurements and then the viewing position and orientation of the range sensor head can be adjusted to scan data from as many views as necessary to completely define the workpiece surface. Both experimental results prove this novel method is more accurate than the traditional three spheres method.

2. Geometric transform method for hybrid system unification

Multi-sensor data fusion in dimensional metrology can be defined as the process of combining data from several information sources (sensors) into a common representational format in order that the metrological evaluation can benefit from all available sensor information and data [11]. The optical scanner and the CMM work in their own separate coordinate systems. If the integrated system is to produce useable results, these two coordinate systems have to be unified.

The same position surface data of a workpiece scanned from an integrated system can be seen as a kind of rigid body movement, so the geometric transformation method can be used to deal with coordinate unification. Since three non-collinear points can express a complete coordinate frame, data transformation of the two systems will be achieved simply with three different reference points and a three-point alignment coordinate transformation method can be used to deal with coordinate system unification. Therefore, the system unification problem for optical system and CMM is converted to coordinate transformation problem, the coordinates of multiple scan data from both system can be transformed to one coordinate system. Coordinate transformation of 3D graphics includes geometric transformations of translation, proportion and rotation. The coordinate transform method by three points is derived by Mortenson and presented in [23].

3. Calibration board design

Since the error of each measuring reference point can be seen as equal weight value, the data fusion errors can be seen as average distributed errors [23]. It is usually very difficult to obtain the same reference point from two different sensors (tactile and optical sensors in this case) because of different measurement principles and methods of two systems as well as different point cloud density. If we take a reference feature point as the calibration reference point every time, the possibility of occurrence of system error, human errors and accidental errors will increase greatly. Because three points can establish a coordinate, we can consider calculating the centroid of a standard calibration ball and then use the sphere centre coordinate as the datum reference point coordinate to achieve data fusion and reduce fusion errors.

The data fusion of 3D measurement data from different systems will be achieved through the alignment of three datum sphere centre points. In fact, the data fusion problem is, therefore, converted to a coordinate transformation problem. The transformation is determined by comparing the calculated coordinates of the centres of the calibration balls obtained in measurement conducted by the optical system.

An expensive ball–plate calibration board (see Fig. 1 (a)) with nine spheres attached to it is created for data fusion of the hybrid system. Three spheres A_1, B_1 and C_1 form an approximate equilateral triangle and three groups of spheres form three small approximate equilateral triangles. The spheres are made of solid polypropylene with a matt finish and have good roundness and sphericity (see Fig. 1(b)). Their nominal diameter is $\Phi = 25.4$ mm with a form error no greater than $\Phi = 30$ μm.

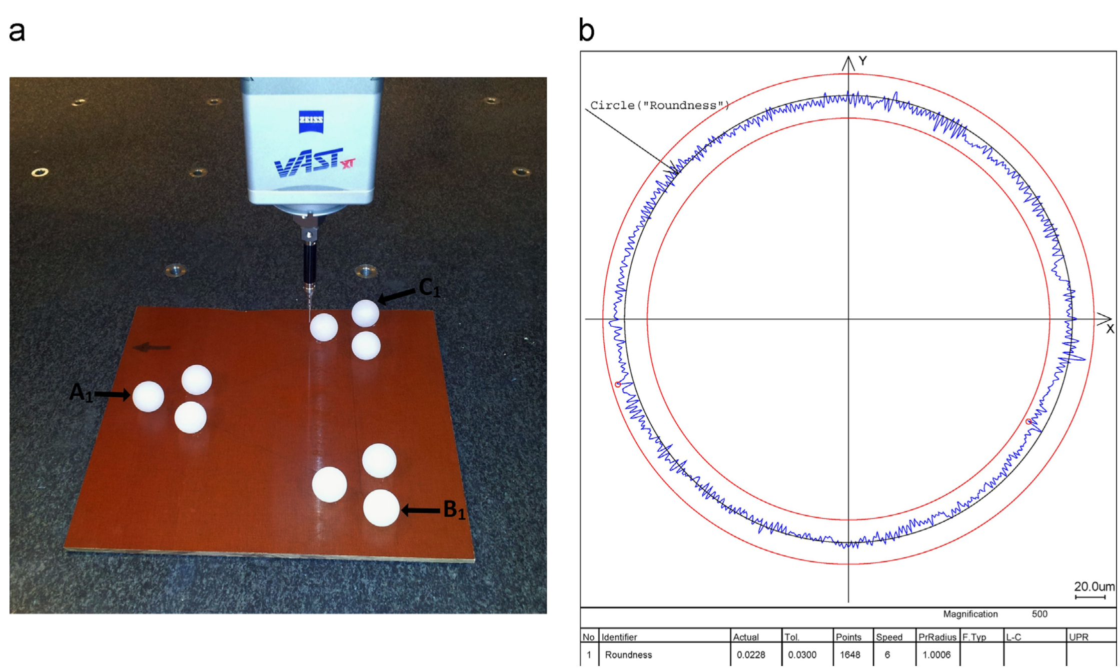

Fig. 1. Spheres calibration board: (a) calibration board on CMM and (b) representative roundness of calibration balls.