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INTEGRATED TACTILE AND OPTICAL MEASURING SYSTEMS IN THREE DIMENSIONAL METROLOGY

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ABSTRACT

Abstract: Coordinate measuring machine (CMM) technology is widely used in inspection, but sometimes it is not suitable for measuring complex parts in dimensional metrology or reverse engineering owing its inherent slow speed. On the other hand, optical scanning sensors acquire data rapidly, but have poorer accuracy and access restrictions. Multi-sensor systems allow selection of discrete probing or scanning methods to measure part elements. The decision is often based on the principle that tight tolerance elements should be measured by contact methods, while other more loose tolerance elements can be scanned by optical sensors. This article summarizes recent developments and applications of hybrid tactile and non-contact 3D measuring systems and gives examples of its applications in dimensional metrology. Recent and future developments will concentrate on improved measuring reliability, reduced uncertainty of measurement data and higher accuracy and lower costs.

Keywords Dimensional metrology, CMM, Sensor, Hybrid systems

1 Introduction

The Coordinate measuring machine (CMM) measurement method is nowadays wide-spread in industrial dimensional metrology but the digitisation process is very time-consuming where high data density is required. An alternative approach is represented by non-contact digitisation of surfaces based on optical techniques, such as time-of-flight lasers, laser scanning, stereovision and structured light. These optical instruments can efficiently capture dense point clouds in terms of speed and reduces the human labour required, this makes them a common choice in reverse engineering applications and quality control of free form objects. However, in comparison to touch trigger probing, non-contact methods in general are considered to be less accurate and sensitive to issues almost irrelevant to tactile based methods. Surface colour, shininess, transparency and other surface properties influence the measurement result. Optical scanners also suffer from occlusions that make certain features difficult to measure. With the goal of cost reduction of standard measurements, an alternative in the field of dimensional metrology is to equip a CMM with different types of sensors in order to exploit the different advantages that each of these sensors have. Particular features of a workpiece can be measured with the most suitable sensor, and measurements with small uncertainty can be used to correct data from other sensors which exhibit relevant systematic errors but have a wider field of view or application range[1].

2 Sensors technologies in dimensional metrology

According to whether the probes or sensors contact the surface, the data acquisition methods can basically be divided into two categories: tactile measurement methods and non-contact measurement method.

2.1 Tactile sensors

2.1.1 Co-ordinate Measuring Machine (CMM)

CMM is a kind of large scale and precision coordinate measuring instrument[2]. Traditionally a CMM is used for measuring geometric features (bores, pockets, size, location, etc.), now it is also used for measuring freeform surface. The main advantages of CMM are high precision and adaptability. A disadvantage of this method is that it may take a long time to measure each point because the process of approaching the surface and withdrawing has to be repeated for each point to be probed. In scanning mode the touching element is guided on a line along the surface while a set of coordinates are sampled in a time sequence, the stylus is all the time in contact with the surface. The interaction with the workpiece causes a mechanical filtering of the surface and surface zones might not be measured if the tip of the stylus has more than one contact point and sharp edges or peaks might lead to smoothed approximation of the surface. A large surface must be built from a raster of many such scans. Another drawback of a CMM is that it cannot measure soft objects because of its contact measurement character.

2.1.2 Chromatography

The chromatography method[3] needs to fill the prototype parts first, then use a combination of layer milling and layer optical scanning method to get internal and external cross-section profile2D data, then combine the 2D data to obtain 3D data. The advantage of chromatography method is it can measure the workpiece's internal and external contours with any shape and structure, but the measurement method is destructive.

2.1.3 Trigger Probe mounted on articulated arm

Manual Coordinate measuring Arm has been equipped with a wide range of probing systems for touch trigger measurements and continuous scanning. Its flexibility makes this measurement arm the perfect partner for a wide range of measurement tasks. The FARO Edge[4] is a an example of portable measurement arm that allows manufacturers to verify their product quality by performing inspections and reverse engineering via hard probing and non-contact laser scanning.

2.2 Optical sensors

As an alternative to tactile data acquisition, optical sensors and computed tomography are being used to an increasing extent. Optical metrology can acquire a high density of point data from the surface with rapid speed. Its non-contact nature makes it suitable to capture the surface of flexible and soft materials. However, optical methods also have their limitations, such as lower accuracy compared to tactile sensors, occlusion and limited viewpoint, as well as sensitivity to optical surface conditions such as specular surfaces or transparent objects. Additionally, the data acquired by optical sensors is often noisy and imperfect and can show redundancy in some areas and missing data in others. The achievable accuracy of a given optical sensor strongly depends on the interaction between the sensor principle and the surface material or the geometric structures.

2.2.1 Laser Scanners

Triangulation sensors are frequently employed for in-process metrology, reverse engineering and coordinate metrology, e.g. for the measurement of complex freeform surfaces such as car bodies in the automotive industry. The measuring area of common laser triangulation sensors (1D-sensor) range is ±5 to ±250 mm, and accuracy is about 1 part in 10,000 and measurement frequency of 40 kHz or higher. An extension of the triangulation principle is known as laser line sensor (2D-sensor), where – instead of a single spot – a line is projected onto the specimen.

In the laser triangulation scanning system[5], the laser projector emits a laser plane and projects it on a part, the CCD detector captures the image of the modulated strip, and the 3-D data on the stripe can be derived and calculated from the image. In general, the laser scanning sensor need to progressive-scan to realize the measurement of the entire surface.

2.2.2 Structure Light Scanners

Fringe (structured light) projection (3D-sensor)[6] can be seen as a kind of extension of 1D- and 2D-triangulation sensor, it can digitise the complex surfaces with a high point density at even faster speed. To clearly calculate the height information, a sequence of different fringes is projected onto the surface (e.g. “Graycode”) which makes a reliable correspondence between the projected and detected fringes. Additionally, using the “Phase shift” algorithm a higher resolution and measurement accuracy compared to the temporal phase shifting method can be achieved.

Fringe projection systems are applied in a large variety of industrial measurement tasks such as prototyping, copying of objects, roughness measurement and quality control. The typical measurement volume for a single-shot fringe projection system lies in the range of 100 × 100 × 30 mm up to 1000 × 1000 × 300 mm. The measurement volume is generally restricted by physical limitations such as reflectivity of surface material and the illumination power of the fringe projector. In practice fringe projection can achieve an accuracy of about 0.05-0.1 mm in a measuring volume of up to 1000 × 1000 × 300 mm. Uncertainty contributions depend on factors such as phase measuring errors, the optical aberration of the lenses and the calibration method used.

2.2.3 Photogrammetric Surface Measurement

Photogrammetry[7] is a metrology technique in which the geometry of objects are determined from fusion of multi-view measurements made on two-dimensional images. It can also be classified as a passive triangulation principle, where three dimensional coordinates of points of interest are calculated via optical triangulation from two or more images taken from different locations. Close-range photogrammetry, commonly called vision metrology, is in the main method for using this to generate the three-dimensional coordinates of a point in object space.

The main advantage of photogrammetric matching is the possibility of observing dynamic scenes. In the case of moving image sensors and/or moving or deforming objects, synchronised imagery can be acquired that enables the reconstruction of surfaces even under highly dynamic circumstances. Example applications are car body deformations in crash testing and the 3D measurement of airbags during instantaneous inflation. Dynamic, shape-varying surfaces cannot be readily measured by any of the sequential or scanning methods such as fringe projection or laser scanning.

2.2.4 Other non-contact sensors

In addition to the above-mentioned non-contact sensors, other optical techniques have also been developed for measuring 3D shape recently, such as Time-of- flight-based pulsed-laser 3D imaging sensors[8], Conoscopic Holography[9] and Computed Tomography[10]. They can be classified as point-sensors (1D-sensors), line-sensors (2D-sensors) and areal-sensors (3D-sensors)[11]. These optical sensors have different working principle and accuracy, so they can be used in different occasions. The achievable accuracy of a given optical sensor strongly depends on the interaction between the sensor principle and the surface material or the geometric structures which have to be measured[1].

2.3 Sensor capabilities and influences

Optical metrology can acquire a high density of point data from the object surface with rapid speed. Its non-contact nature makes it suitable to capture the surface data of flexible and soft materials. However, optical methods also have their limitations, such as lower accuracy compared to tactile sensors, occlusion and limited viewpoint, as well as sensitivity to optical surface conditions such as specular surfaces. The data acquired by optical sensors is often noisy and imperfect and can show redundancy in some areas and missing data in others.

Overall, 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 applications.

While fusing data sets obtained in different sensors, 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. Factors which influence this can be shape and roughness of probing systems, the direction of probing or the optical and mechanical characteristics of the workpiece.

3 Tactile and optical multisensory coordinate metrology

The reduction of the lead time in dimensional metrology, and the increased requirements in terms of flexibility and level of automation of the whole digitization process have resulted in a great deal of research effort aimed at developing and implementing combined systems for the reverse engineering based on cooperative integration of inhomogeneous sensors such as mechanical probes and optical systems.

3.2 Integrated laser and CMM systems

The optical system can be a simple video-camera, which acquires the global shape information and provides the CMM with the exploration paths of the tactile probe or other sensors[12, 13]. Such systems, of which two are to be described in more detail, combine the strength of a vision system, the ability to quickly generate global information, with the strength of a touch probe, the ability to obtain highly accurate measurement information (see Figure 1). The information generated by using the vision system is fused with data generated by the machine scales and the probe. The fused information is used to guide the movement of the touch probe as it performs an inspection scan across the surface of a part. This allows parts to be measured even if an accurate a priori model is not available.

An intelligent integration of the information from the optical and the contact sensors on the signal level allows the rapid reconstruction of objects of complex geometry[14]. Additionally a competitive fusion approach results in a higher accuracy for the digitization of the object. The starting point is the acquisition of a number of clouds of points using the 3D vision system. Each one provides initial dimensional information about the object. The initial CAD model of the surface is then determined to be used as first approximation for CMM programming. The a priori knowledge of an approximate surface model allows efficient programming of the scanning and digitizing path of the CMM mechanical probe, with a reduction of the number of touch points. The measured data are then imported back to the CAD environment and used to produce the final, accurate CAD model[15].

3.2 Integrated laser and CMM systems

Instead of a vision system laser scanner data can also be applied[16-18]. With its high data sampling rate the sensor is suitable to detect the large point cloud data files required to define freeform surfaces, whereas a CMM touch probe's accuracy is used to precisely define the boundary of bounding contours. Both sensors are mounted on the z-axis arm of a computer controlled CMM (see Figure 2). The data produced by each sensor is referenced to an identical origin and axes in the work volume of the CMM. Therefore the laser sensor and touch probe data are subsequently referenced to the same coordinate system. Typically, a cloud data set is obtained, by the laser sensor head, from the entire object surface and then transferred to the workstation where the overall cloud data file is constructed. The viewing position and orientation of the range sensor head can be adjusted to gather data from as many views as necessary to completely define the object. Each view is treated as a separate record, from which the overall cloud data file is composed. The touch probe data from each surface patch boundary is acquired and accumulated in the CMM personal computer before being transferred to the workstation. The patch boundary data is integrated with the corresponding cloud data file. The fitting process uses the boundary data, collected by the CMM, to define the four bounding B-spline curves for each patch. These curves remain spatially fixed, during the subsequent patch fitting, thereby ensuring the physical edges do not move[16]. Such multiple sensor integration can capture metrologies with 2D and 3D data acquisition by tactile and optical sensor techniques.

3.3 Hybrid fringe projection and CMM systems

To meet the requirement of high speed as well as high accuracy in geometry measurement, the hybrid optical structured light and CMM coordinate measuring system was designed (see Figure 3). It combines the accuracy of contact measurement regarding the identification of measurement points and the speed of full-field structured light optical scanning methods. The novelty of the hybrid system is that both the optical and contact measuring system measure in the same absolute coordinate system which is established on the base of developed standard. This combination of measuring systems enables the measurement of a wider range of objects than for any these systems alone. The limitations of each system are compensated by the other. Measurement results from all of the optical sensors and the CMMs measurement head are combined into one data set. The data is analysed removing unwanted or erroneous points and divided into series of points belonging to individual surfaces. The data from optical sensors are acquired, pre-processed and segmented into individual surfaces by developed 3DMADMAC software. Further, these series are imported to the existing metrological software. For the purpose of data analysis the hybrid system is seen by the metrological software as a single device[19].

3.4 Photogrammetric cameras with tactile probing

The photogrammetry system can combine with a tactile probing, where a hand-held probing device with calibrated local reference points is tracked in 3D space in order to provide the coordinates of the probing tip, to measure single object points. Figure 4(a) describes the principle of single camera probing. The position of the probe is calculated by inverse space resection with respect to a minimum of four control points. The typical accuracy of single object points probing systems is in the order of 0.2-0.5 mm over a range of 2 m.

Photogrammetric sensors can be also combined with additional measuring systems, as seen in fringe projection systems, laser tracking or scanning systems. Figure 4(b) shows a commercial hybrid structured light measuring system with combinations of photogrammetric sensor and tactile probing, which is made by GOM Ltd.

3.5 Additional hybrid non-contact and tactile systems

Due to the need for 3D digitisation and quality control in rapid prototyping and reverse engineering processes, other hybrid solutions are also applied for surface reconstruction. An example is FARO

Edge which is made by FARO Technologies Inc. With a laser line and a trigger probe mounted on an articulated arm, FARO Edge can measure objects at high speed and accuracy.

4 Summary and outlook

Since the requirements on the speed, complexity and accuracy of dimensional metrology are increasing, we need to choose suitable instruments to measure workpiece features and their relationship quickly and accurately. Hybrid dimensional metrology system data acquisition and fusion is used to solve this task. Applications of tactile and optical coordinate metrology in dimensional metrology are of increasing importance in quality control, reverse engineering and many other industrial fields. However, manufacturing and metrology related requirements result in future challenges:

- Multiple data models merging and processing: The fusion methods for the different surfaces captured by contact and optical sensor principles must be part of research and development in order to achieve standardized and commonly acknowledged procedures.
- Uncertainty of multisensor measurements: Solutions and standards must be agreed on for fusion of data from both contact and optical sensor principles of different accuracies.
- Automation: The advantages of hybrid systems will be further developed for the automatic conduction of measurements with homogeneous and inhomogeneous probing systems, guiding of these probes and registration and fusion of the data.

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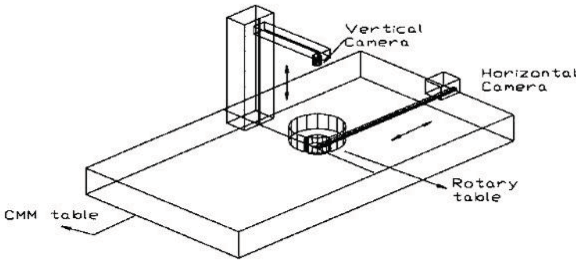


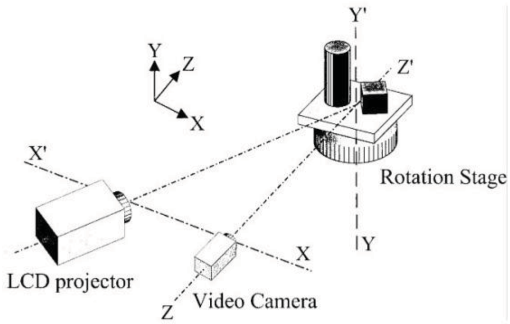


Figure 1: (a) CMM probe and camera **(b) Basic layout of the 3D vision system**

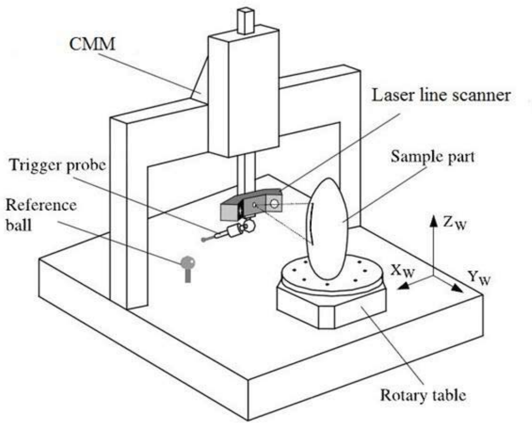
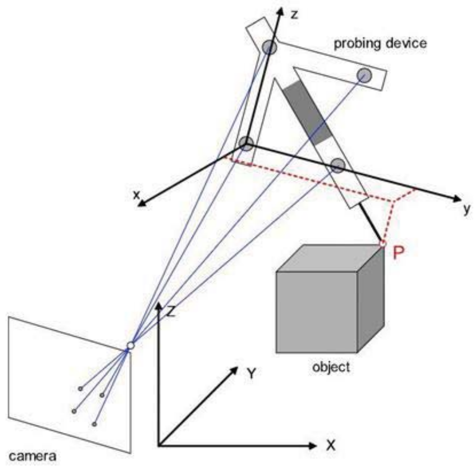


Figure 2: Integrated laser-CMM system configuration

Figure 3: Hybrid fringe projection and CMM system



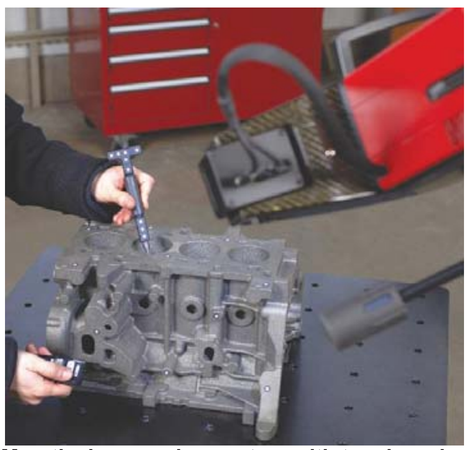


Figure: 4 (a) Principle of single point probing system **(b) GOM optical measuring system with touch probe**