Title:
Multi-Sensor Blue LED and Touch Probe Inspection System

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Introduction:
In coordinate metrology, contact and non-contact measurement methods each have their own respective strengths and weaknesses [3]. Touch-trigger probes can achieve low uncertainty, and perform well inside deep holes, but have low data acquisition speed. In contrast, non-contact digitizers collect high density surface point clouds in seconds, and are much less likely to suffer from sensor collisions with the part, but have higher uncertainty. Development of a multi-sensor inspection system that synergistically conjoins their individual task specific advantages is described herein.

A long standing problem in tactile measurement is the situation when features of sheet metal parts produced at early production stage significantly deviate from CAD nominal. Consequently, Dimensional Measuring Interface Standard (DMIS) inspection paths created using the CAD nominal geometry can no longer be used without introducing significant part surface cosine error. In more extreme cases, missed touches or probe collisions can occur. Existing methods for solving this problem have included taking preliminary sample points around the (hole or other) feature, and then iterating to obtain more accurate results. To solve this more efficiently, a multi-sensor blue LED structured light scanner and touch-trigger inspection system was developed and is reported in this paper. Calibration of the scanner with respect to the CMM was investigated using a designed angled slot target. The nominal touch probe measurement path was fine-tuned after using the scanner data to estimate (hole) feature sizes and positions. Finally, a lightweight 2-axis rotary table was designed for use with surfaces with non-vertical normal directions.

Main Idea:
The scanner was first calibrated with respect to the CMM. Following that, the multi-sensor synergistic inspection and oriented part inspection was performed.

Extrinsic Calibration of the Scanner with Target
To transform the Local Coordinate System (LCS) of the structured light scanner to the CMM Machine Coordinate System (MCS), a target with two angled slots was conceived and manufactured (Fig. 1(a)).

Angular misalignments between the scanner and the CMM axes were mechanically minimized first. For adjusting the roll, pitch, and yaw, a Renishaw® AM1 adjustment module [4] was mounted beneath the target (Fig. 1(b)). Using touch probing, the top plane of the target was adjusted to be horizontal, and the long slot to be aligned with the CMM Y axis. Another AM1 module was mounted between the scanner and the CMM Z axis (Fig. 1(c)). The scanner was adjusted to align with the top plane of the target, and its Y axis with the long slot.

Following that, residual misalignments were corrected mathematically. Firstly, the top plane, the −X and +X 30° angled edge planes of the long slot, and the +Y and −Y 30° angled edge planes of the short slot were all touch probed and scanned to obtain data in the CMM MSC and the scanner LCS respectively. Secondly, using the acquired data, both the CMM MCS and the LCS of the scanner were transformed to the calibration Target Part Coordinate System (TPCS). To construct this coordinate system, the intersection line of the two angled planes of each slot was first calculated, and projected to the top plane of the target. The intersection point of the two projected intersection lines was set as the origin. Top plane normal was set to be Z direction, and projected intersection line of long slot to be Y direction. Finally, the Homogeneous Transformation Matrix (HTM) for transforming the coordinates of the scanner LCS to the CMM MCS was obtained using Eqn. (1).

$$HTM_{LCS\rightarrow MCS} = HTM_{TPCS\rightarrow MCS} \times HTM_{TPCS\rightarrow LCS}^{-1} \tag{1}$$

Fig. 1: Calibration target and Renishaw®AM1 adjustment module: (a) Drawing of target, (b) Target and adjustment module, (c) Sensor and adjustment module.

Multi-Sensor Synergistic Inspection

For synergistic inspection, features, such as holes and slots, were first measured with the blue LED sensor. The approximate geometric and dimensional properties of features obtained from the scanner were then used to adjust the nominal tactile inspection path created from CAD geometry. Finally, the features were touch probed with low uncertainty.

For single setup use, a combined blue LED scanner and touch probe CMM mechanical mount is used (Fig. 2). The synergistic inspection process is as follows:

1. Calibrate the scanner with respect to the CMM using the target.
2. Manually scan a part/fixture teach point with the scanner. Transform the coordinates of the teach point from the LCS to the Global Coordinate System (GCS) of the scanner.
3. Using the CAD model and the information from Step 2, obtain the nominal global coordinates of the features to be measured. Position the scanner over the features, take measurement scanner snapshots, and employ the built-in scanner feature fitting software to get the approximate feature sizes and positions. Then transform the scanner data to the CMM MCS.
4. Measure the same (Step 2) teach point with the touch probe, and translate the CMM MCS and the scanner data to the Part Coordinate System (PCS), the origin of which is the teach point.
5. Fine tune the nominal inspection path for touch probe measurement (created from the CAD nominal) using the actual scanner data, and touch probe to measure the features.

The fixture posts in Fig. 2 are used solely for conveniently locating the sheet metal part. There is no need to spend time measuring the posts to construct the reference coordinate system. When touch probing a hole in thin sheet metal, a common challenge is to determine the height so that measurement points are collected midway through the material thickness. With this multi-sensor approach, the points on the surface around the holes were first collected using the scanner. The average height of surface points within a 1×1 mm^2 square zone adjacent to each planned touch probe hole point was then calculated, and offset by half the material thickness to program the touch probe contact.

Rotary Table and Oriented Part Inspection

To measure surfaces with non-vertical normal, a lightweight 2-axis rotary table was designed (Fig. 2). It consists of a pair of vertical bases, suspend hangers, locking hinges, a bottom plate, a round plate and a ring (*Lazy Susan* style) bearing. The round plate is mounted on the bearing, providing one rotary axis. The adjustable 10^0 angle increment locking hinges provide the second rotary axis. Three tooling spheres mounted on the table provide coordinate system registration for different table orientations.

In oriented part inspection, the part was scanned at different orientations to obtain all the top surfaces with various normal directions, and the tooling spheres were touch probed at each orientation. The scanner data were first transformed to the CMM MCS with $HTM_{LCS \to MCS}$. The spheres centers in CMM MCS were determined using Orthogonal Least Squares [5]. After that, the HTM for registration, $HTM_{Ori \to Hor}$, was obtained by least-square fitting each oriented point set and the horizontal point set of the sphere centers [1]. Finally, the scanner data from different view angles can be merged together into the horizontal point set (Eqn. (2)).

$$P_{MCS}^{Hor} = HTM_{Ori \to Hor} \cdot P_{MCS}^{Ori} \tag{2}$$

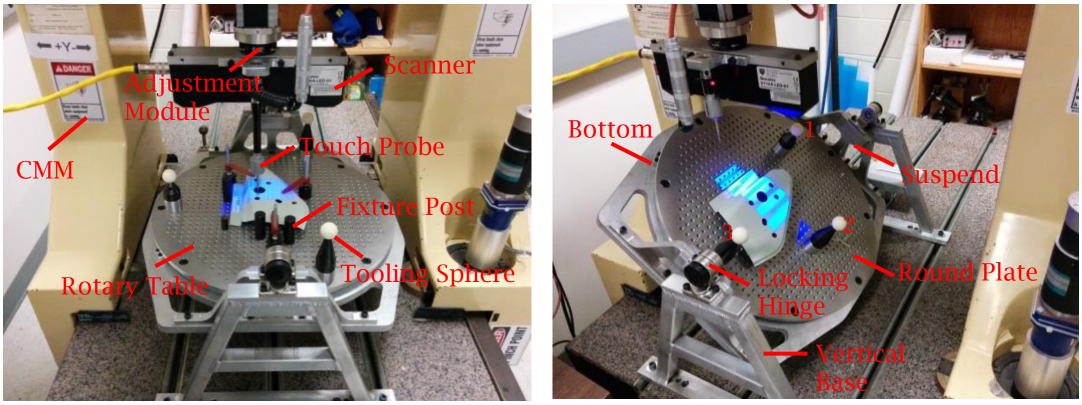

Fig. 2: Multi-sensor system configurations: (a) Horizontal, (b) Oriented.

Hole	CAD Nominal			Blue LED			Touch Probe		
	X	Y	R	X	Y	R	X	Y	R
1	112.012	-57.300	5.000	111.839	-56.805	5.125	111.881	-56.845	4.957
						Converged	111.882	-56.842	4.957
2	101.342	-80.086	5.000	101.105	-79.688	5.126	101.131	-79.787	4.959
						Converged	101.133	-79.785	4.960
3	49.128	-58.540	5.000	49.024	-58.161	5.128	48.959	-58.268	4.949
						Converged	48.959	-58.268	4.950
4	76.738	-62.618	11.000	76.493	-62.195	11.202	76.547	-62.277	10.963
						Converged	76.547	-62.273	10.963
5	34.714	-126.508	5.000	34.739	-126.112	5.130	34.792	-126.148	4.971
						Converged	34.793	-126.148	4.971

Tab. 1: Measurement results of horizontal sheet metal automotive part (mm).

Experimental Results

For the horizontal table orientation, the five holes of the sheet metal automotive part were measured with this multi-sensor approach (Fig. 2(a)). The hole positions and sizes obtained from the CAD nominal geometry, the blue LED scanner, and the touch probe are presented. The tactile measurements were iterated four times by starting with the scanner results. For brevity, only the initial and the converged tactile measurement results are shown in Tab. 1. From the table, it is observed that the actual positions of the holes (the converged results) deviate as much as 0.5 mm from the CAD nominal geometry, but only up to 0.1 mm from the scanner data. Tab. 1 also indicates that even the initial tactile measurements are within 4 µm of the converged results, which implies that the iterating process can be reduced or eliminated for typical sheet metal tolerances.

The sheet metal was scanned at four orientations (Fig. 3), beginning with the horizontal orientation. Using the locking hinges, the table was rotated ~±40˚. Finally, the round plate of the rotary table was rotated ~90˚ with the ring bearing when the table was at ~−40˚. The tooling spheres were touch probed at each orientation, and the centers were recorded. Point clouds were compared with each other, and the merged point cloud was compared with CAD nominal geometry employing software Geomagic Qualify 12 [2]. Deviation of points was obtained from the comparison result.

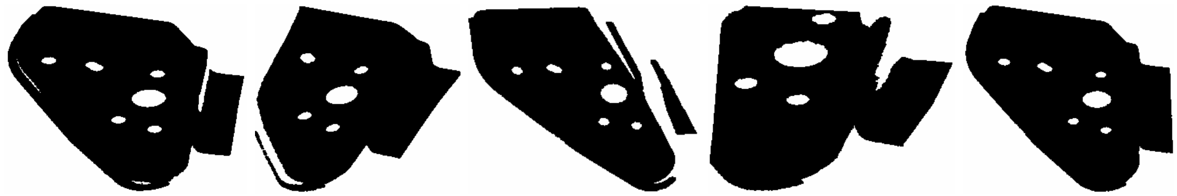

Fig. 3: Digitized point clouds of the sheet metal from four orientations: (a) Horizontal, (b) ~+40˚, (c) ~−40˚, (d) ~90˚ at ~−40˚, (e) Merged cloud of all orientations.

Conclusions:

The multi-sensor inspection system takes advantage of both the low uncertainty of the touch probe and the high digitizing speed of the blue LED structured light scanner. Complementary and synergistic interactions can both be implemented in the system. The synergistic interaction of the system saves measurement time, and avoids probe collision. The angled slot calibration target can be used for calibrating the scanner with respect to the CMM. The rotary table facilitates the scanning of a surface with non-vertical normal. This system can be implemented not only on an orthogonal CMM, but also on portable CMMs and CNC machines without extensive electronic interfacing. Ongoing work will focus on refining the transformation mathematics, and further verification using an analog probe CMM.

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