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A non-contact automatic measurement for free-form surface profiles

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This paper describes the process of developing a non-contact type automatic measurement system for any free-form surfaces on a CNC coordinate measuring machine (CMM) or a CNC machine tool, and its CAD/CAM integration. A laser probe, made by Keyence Co. model LC-2220, was integrated into the CNC machine as the non-contact sensor. Extensive calibration work has been carried out on the systematic accuracy of the laser probe with respect to the color, material, surface slope, and edge detection of the workpiece through the use of a HP5528 laser interferometer system. Measurement software has been developed for automatic surface tracing of any free-form profile. Having employed the surface painting technique, the shape error of the copied object relative to its master piece was found to be within 30 μm, which has been deemed adequate for the mold industry.

Keywords: non-contact measurement, laser probe, free-form surface, coordinate measuring machine

Introduction

Since the first coordinate measuring machine (CMM) was developed by the Ferranti company of UK in the 1960, the measuring efficiency of dimensional metrology has been greatly improved in the industry. Conventionally, most CMMs are equipped with the touch-trigger probes for a contact type of measurement on geometrical elements, such as line, plane, circle, cylinder, sphere, cone, etc. The measuring process is indeed very fast and repeatable with respect to the above elements, since it requires only a limited number of probing points, and the probe radius compensation is quite straightforward. However, as the demands for 3-D free-form surface measurements have increased in recent years, especially by the mold industry for reverse engineering, many disadvantages have been discovered when applying the contact probe for numerous measuring points. Some typical problems are:

- the speed is not fast enough due to repetitive motion into and out of the surface;

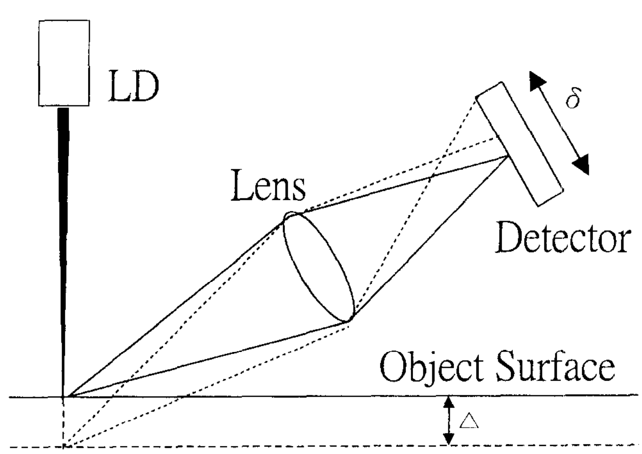

Figure 1 Laser triangulation principle.

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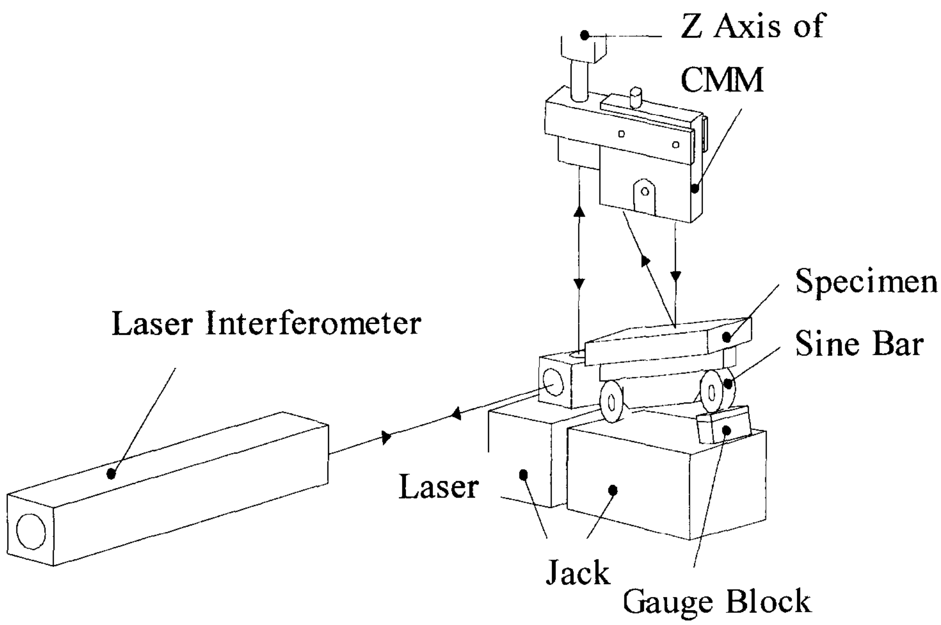

Figure 2 Experimental set-up for laser probe accuracy calibration.

Table 1 Effect of surface slope on the laser probe accuracy (material, bakelite; range ±2 mm, unit, micron)

Slope (degree)	0	10	30	45	60
Max. average error	−18	−14	−30	−69	−98
Max. reversal error	1	1	1	1	1
Max. standard deviation	1	2	2	2	2

Table 2 Effect of painting color and surface slope on the laser probe accuracy (material, aluminum alloy; range ±2 mm; unit, micron)

Color	Original	White	Red	Yellow
0 degrees	−24	3	4	4
30 degrees	76	−6	4	8
60 degrees	90	36	−6	−24

Table 3 Effect of painting color and surface slope on the laser probe accuracy (material, steel; range ±2 mm; unit, micron)

Color	Original	White	Red	Yellow
0 degrees	−12	−5	7	8
30 degrees	98	−28	6	−17
60 degrees	120	59	−23	−25

- the sampled position is affected by the probing speed;
- the sampled points may not be adequate to represent the measured surface accurately;
- the technique of probe radius compensation is more difficult;
- the probe tip is subject to be worn quickly; and
- some dynamic errors of the machine structure and the servo controller may occur.

In order to improve the above-mentioned drawbacks, some laser probes have been developed for non-contact measurement of free-form surfaces in recent years[1–4]. In addition, when applying this kind of probe to the CNC type of CMM, the system accuracy and the measuring speed can be significantly increased[5,6], and the CAD/CAM integration can be easily achieved for the purpose of reverse engineering[7–9].

This paper describes the process employing a low-cost laser probe to a DCC (direct computer controlled) type CMM to develop an automatic non-contact measuring system for 3D free-form surfaces, and its integration with some PC based CAD/CAM software for reverse engineering. The same technique was also applied to a CNC machining center to build an on-machine measurement system. An in-depth calibration of the laser probe was primarily investigated with respect to the material, the surface slope, the color, and the edge detection of the workpiece to be measured. After employing the surface painting technique, the shape error of the reproduced workpiece relative to its master was found within 30 μm, which is deemed adequate to meet the requirement of the mold industry.

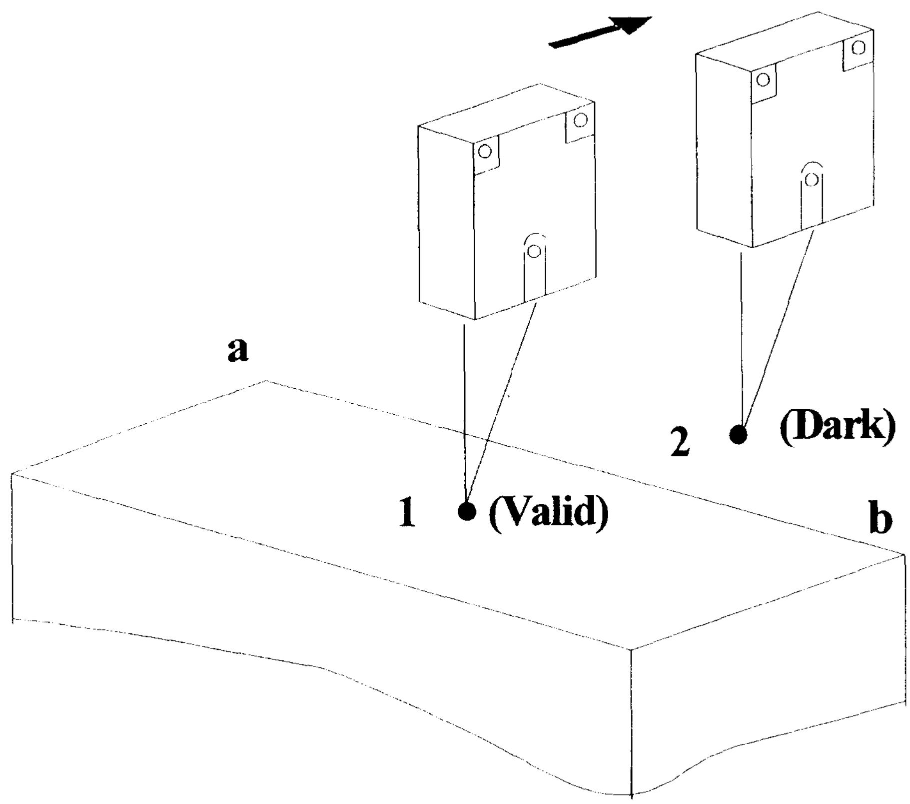

Figure 3 Laser probe motion for edge detection.

Operating principle of laser probe

The laser probe used in this study is a Keyence LC-2220 sensor head with an LC-2100 controller. This low-cost and visible laser probe provides displacement measurement via the laser triangulation technique. As seen in *Figure 1*, the focused laser beam emitted from the semiconductor laser is projected onto the object surface. Due to the surface roughness, the reflected beam will be scattered and partly collected by the receiving lens. Through this lens, the beam will be focused and projected onto the position sensitive detector (PSD) in the sensor head. If the object to be measured moves (Δ, in the figure), the reflected laser light spot also moves (δ), which can be detected by means of the PSD. Then, this spot displacement is converted to an analog or a digital signal through a data-processing unit, which is also called the controller here. Finally, the controller carries out data processing, such as linearity compensation and average value calculation, displaying and outputting the measured results.

Performance tests of laser probe

Performance curves for all of the non-contact type displacement sensors, such as the eddy current type,

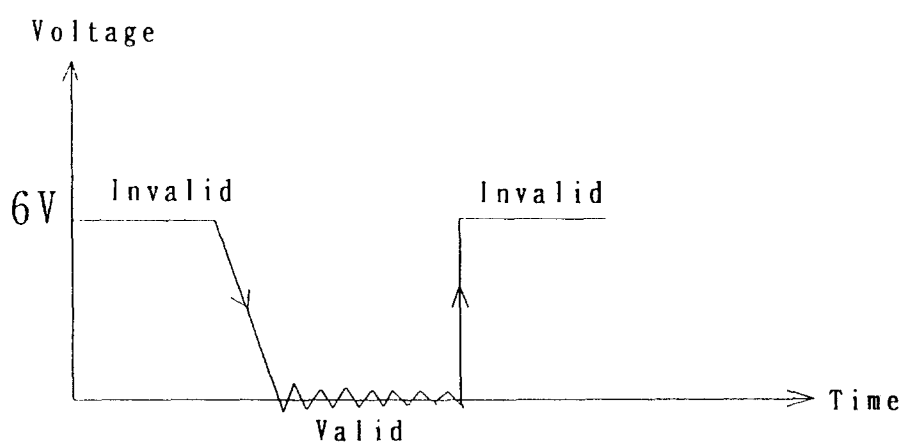

Figure 4 Output voltage changes of laser probe across the edges.

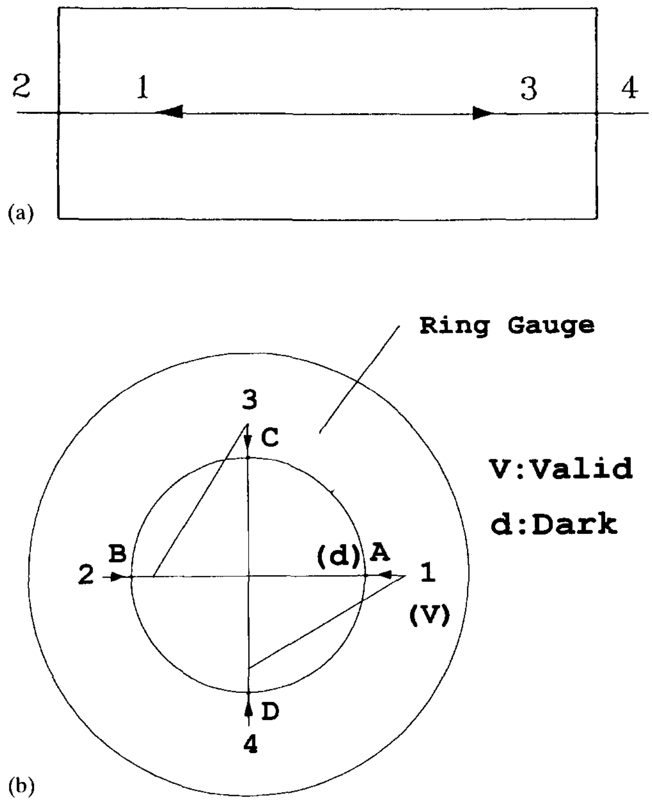

Figure 5 (A) Proposed probe path for length measurement. (B) Proposed probe path for circle measurement.

the ultrasonic type, the pneumatic type, and the laser beam reflected type are related to the surface properties of the tested objects. Some important parameters of the surface property with respect to the laser probe may include the material, the color, the roughness, and the slope of the object surface. Most of the specifications of laser probes, however, are not adequately described in the operational manuals. The listed data reflecting the performance characteristics of any particular laser probe provided by the manufacturer usually are not directly applicable to a particular object to be measured[10]. Therefore, primary accuracy calibration of the adopted laser probe with respect to the adopted workpiece has to be carried out in order to ensure more accurate measured results[11,12].

System set-up for laser probe calibration

Figure 2 shows the experimental set-up for this laser probe calibration system. The laser probe to be calibrated was mounted on the spindle head of a coordinate measuring machine (CMM, DCC type, Numerex Co.). The tested specimen was placed on a sine bar. The angle and the elevation of the sine bar can be adjusted by the gauge blocks and the jack respectively. A HP5528 laser interferometer was adopted to provide reference displacement in comparison with the laser probe output. The spindle could be moved up and down step-by-step by the computer commands. Therefore, once initiated, this calibration task could be processed automatically according to the VDI 3441 standard[13], and five times bi-directional travels were executed for each task. Various experiments were then investigated in sequence by changing different specimen conditions, such as materials (steel, aluminum alloy, and bakelite), slopes (0 to 60 degrees in steps), colors (original, and white, red, yellow paintings), and surface roughnesses (0.4 μm to 3 μm).

The effect of surface slopes

Numerous calibrated data were collected with respect to different surface slopes. The first experiment was carried out on a specimen made of bakelite in its original color (brown). The linearity is calculated with respect to the least-squares line. *Table 1* summarizes five tested results with different surface slopes. An interesting phenomenon can be seen, namely, that as the surface slope increases the displacement error increases too. It can be explained that the scattered light on the object surface performs a Gaussian distribution along the specular direction[14]. As the surface normal is moving away from the laser beam axis, the intensity of the reflected beam collected by the light receiving lens in the sensor head is decreasing, which will result in a low signal-to-noise ratio (S/N). Consequently, the linearity will get worse. However, fortunately, the repeatability still remains as good as before.

The effect of surface materials and colors

Similar studies were also carried out with respect to an aluminum alloy specimen and a steel specimen separately. In addition the influence of surface colors on the laser probe's performance was studied by uniformly painting different colors on the tested surface. *Table 2* summarizes calibrated results of the laser probe with respect to the aluminum alloy at different slopes and in different surface colors. A significant phenomenon was found here that, regardless of the changes in the surface slope, the red surface could always ensure the laser probe performed accurately. It can be understood that the red surface responds better to the red beam in terms of the reflectivity than the other colors. As the aluminum alloy specimen was replaced by the steel specimin, a similar conclusion was obtained, as seen in *Table 3*. From these studies, a suggestion can be given to the mold-making industry that, while producing the mold through the reverse engineering technique with a laser probe, the measuring accuracy can be significantly improved if the master piece is coated with red paint or filmed with red color if the surface is not allowed to be painted.

The effect of surface roughness

The influence of the surface roughness of the workpiece on the laser probe measurement had already been investigated previously[15]. It was found that within the reasonable Ra values (0.4 to 3 μm) of any machined surface, the calibrated results did not show significant changes as long as the optical plane of the laser probe was perpendicular to the surface lay. Since most of the workpieces to be measured must have been initially polished to certain small Ra values, this effect could therefore be neglected.

Enhancement of edge detection capability of laser probe

Most of the laser probes on the market provide only the function of displacement measurement. Although this function can make the technique of surface scanning measurement possible, the capability of most laser probes in edge detection is still currently very poor. Some solutions in this technology will have to be produced since any geometrical shape of the workpiece must have a boundary. A method for this aspect is therefore proposed in this work.

The investigated laser probe, Keyence LC-2220 sensor head with an LC-2100 controller, has both digital and analog output ports. The digital port transmits its digital readouts to an external device via a RS-232C or a GPIB interface. Meanwhile, the analog port sends a voltage value in proportion to the meter reading out to an external A/D converter. As the laser probe is out of its measuring range, the invalid region, the digital readout (DRO) will appear as a 'DARK' signal and the analog port will produce an output of 6.55 volts. As the laser probe is located

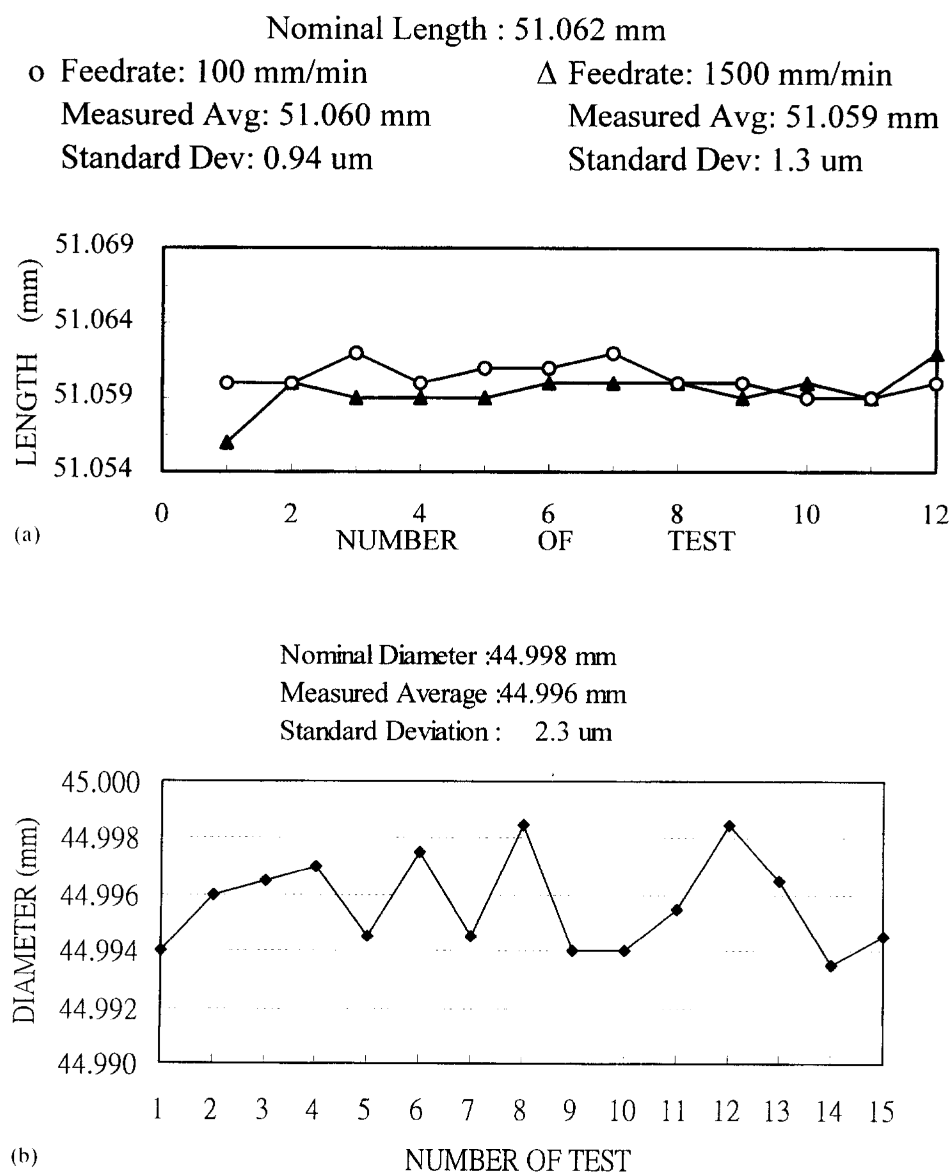

Figure 6 (A) Tested results of a length measurement. (B) Tested results of a circle measurement.

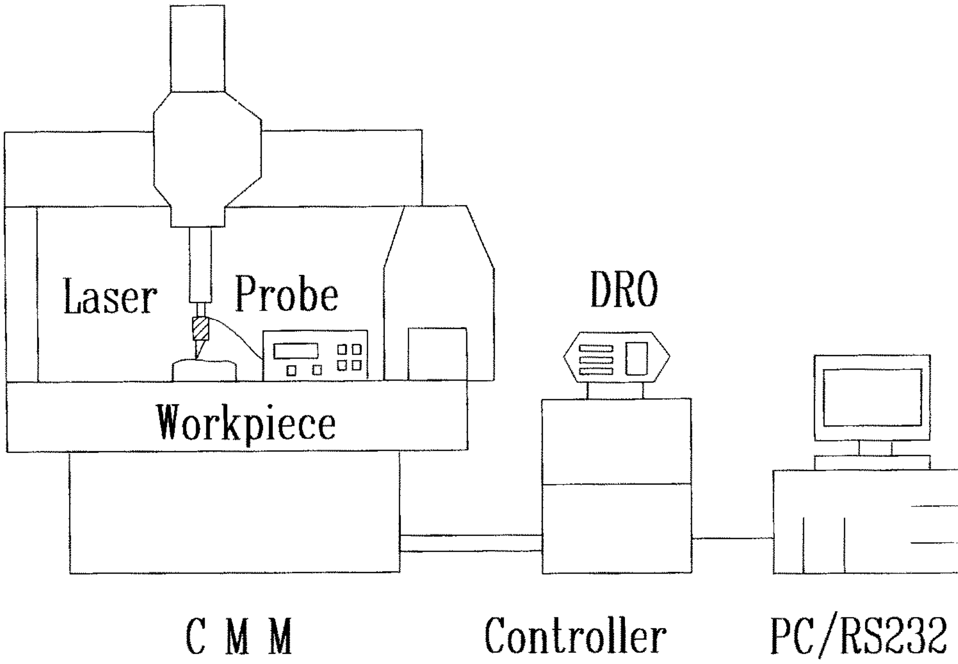

Figure 7 Integration of the laser probe into a CMM.

within its valid region and at its reference distance (the stand-off distance) to the surface, the analog signal will produce an output of zero volts.

An initial experiment was carried out by setting the laser probe on the CMM at its reference distance to a flat work surface. It was then repeatedly moved in and out of the surface horizontally, as seen in *Figure 3*. The voltage changes of the analog signals were observed by a digital oscilloscope. *Figure 4* shows a typical display of the voltage changes when crossing the sharp edge of the work surface. It was clearly seen that when moving the probe from the invalid region into the valid region across the sharp edge, the output signal experienced an apparent time delay, which was proportional to the feed-rate. However, when moving the probe from the valid region to the invalid region, the output signal responded immediately at the edge position. This phenomenon is difficult to explain. Yet, the authors believe that it could be due to the triangulation principle of the laser probe. However, these results point out a feasible solution. The edge detection should always be done from the valid region to the invalid region. Another important factor should also be pointed out here; namely, that during motion the optical plane must be perpendicular to the surface lay, otherwise the light will be seriously scattered.

To verify this enhanced capability of the laser probe in edge detection, dimensional measurements were carried out on a line and a circle separately. *Figure 5*a and *Figure 5*b show each proposed measuring path. *Figure 6*a and *Figure 6*b plot the

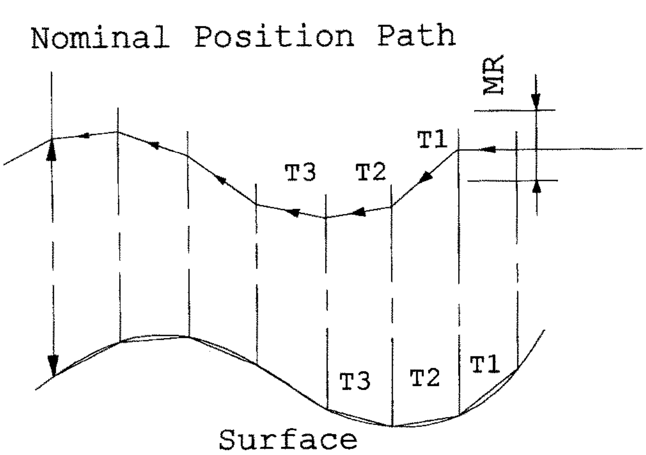

Figure 8 Continuous path for surface tracing.

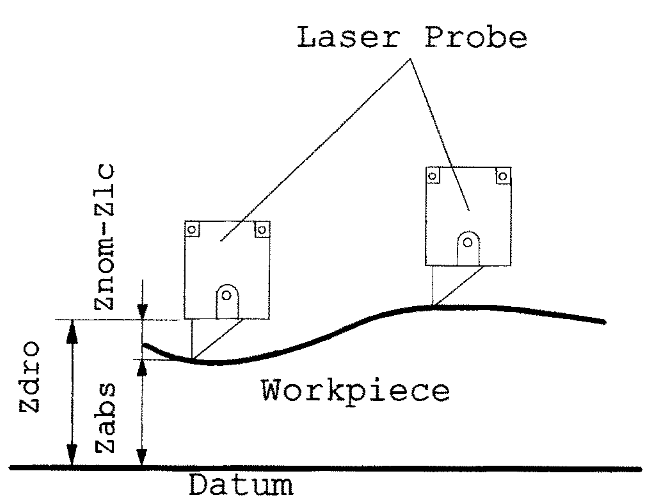

Figure 9 Relationship between the laser probe readout and the CMM readout.

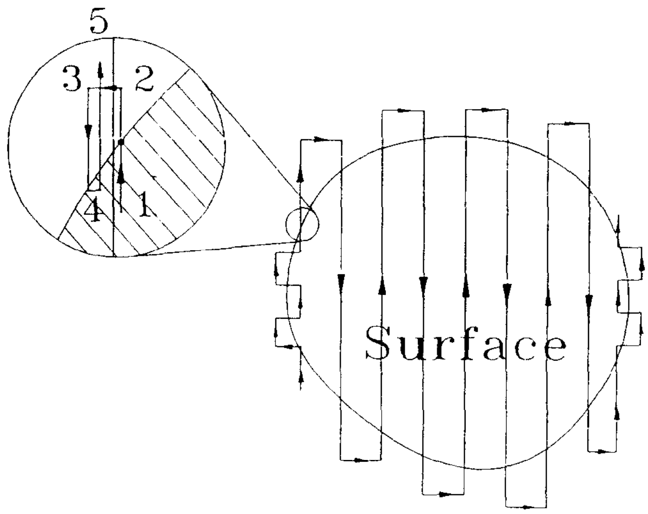

Figure 10 Scanning path on an arbitary work surface with edge detection.

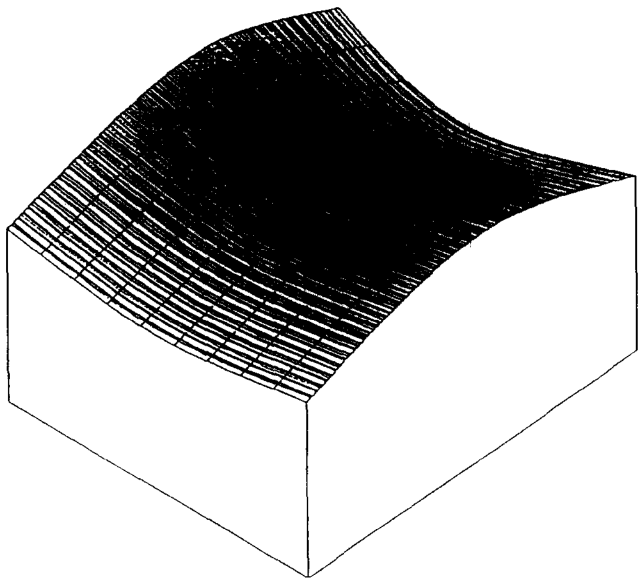

Figure 12 Measured profile plotted by the surface SurfCAM software.

measured results, which are all quite consistent with the corresponding nominal dimensions.

Development of a laser scanning measurement system on CNC machines

Set-up of system hardware

Two types of hardware systems were developed. The first one was used to mount the laser probe on a DCC type CMM as a non-contact probe. Since the communication commands of the DCC controller had been provided by the manufacturer, the CMM could be entirely controlled by an external computer, the IBM PC. The analog output of the laser probe was linked directly to the CMM's probe head PH1 to provide the triggering signal for edge detection. Simultaneously the RS-232C output of the probe was sent directly to the computer to provide the height reading of the work surface. This system configuration is shown in *Figure 7*.

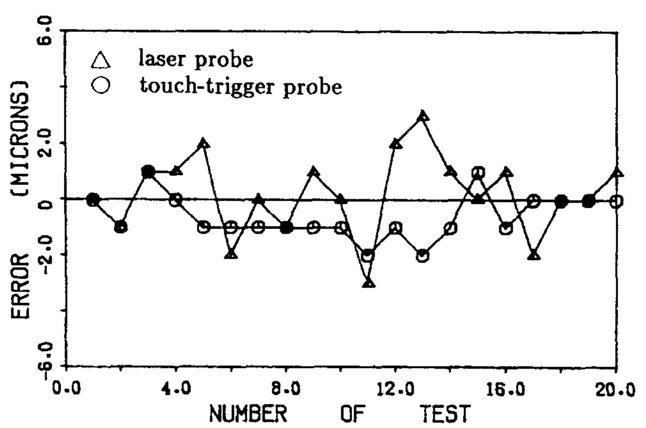

Figure 11 Comparison of laser probe and touch-trigger probe measurements.

The second type of hardware system was to mount the laser probe on the spindle head of a CNC machining center. The machine position was continuously detected by a 3-axis counter card that could read the encoder's feedback signals of all three axes. The laser probe gives its readings to the computer via the RS-232C interface. The edge detection was done while the computer read the 'DARK' signal. The motion commands of the machine tool were given by the computer, in NC codes, through the RS-232C.

Automatic surface scanning techniques

From the calibration results of the laser probe, the measurement range of this type of probe was known as ± 2 mm from the reference distance, and the best reflective color of the surface was red. The work surface was therefore initially painted with red paint. During measurement, the free-form surface of the workpiece was scanned by the laser probe in the line-by-line sequence along a prescribed axis, usually the X-axis, of the machine. Since the variation in the surface heights might sometimes exceed the measurement range of the laser probe, the vertical position of the laser probe had to be automatically adjusted by the computer during scanning to ensure that the readings were always within the valid region. To meet this requirement, a surface tracing technique called the continuous tracing path was developed. During measurement, the slope of the just measured surface was continuously calculated for the prediction of the following motion vector($\mathbf{T}_i$) to the next target, as shown in *Figure 8*.

$$\mathbf{T}_i = Z_{abs}(i+1) - Z_{abs}(i) \quad (1)$$

where $Z_{abs}(t)$ denotes the measured absolute position at the ith target. Since all the free-form surfaces must

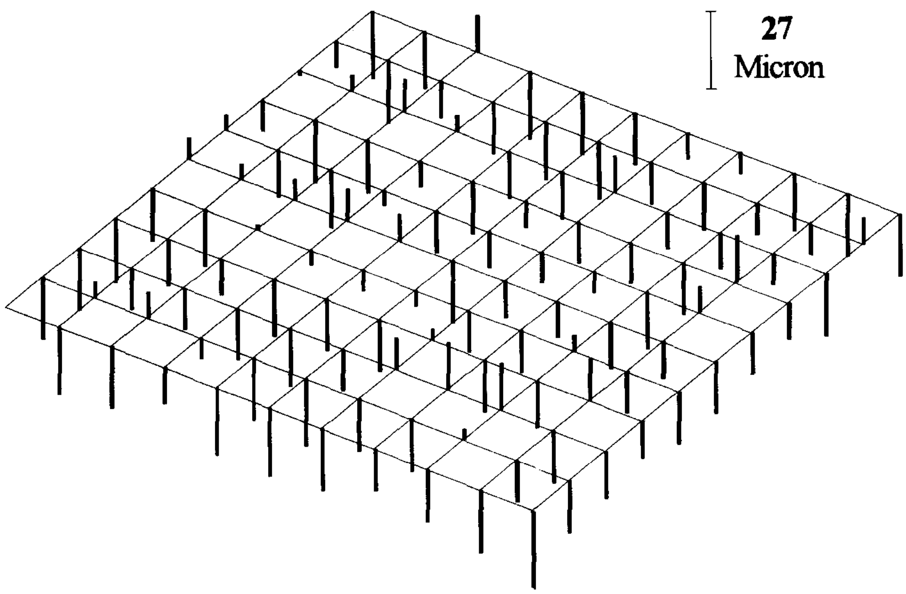

Figure 13 Shape error of the copied surface.

obey the C^2 continuity (second order continuation), this kind of tracing path can always allow the laser probe to be located in its own measurement range. The motion path of the laser probe thus performs a continuous shape.The relationship between the laser reading and the probe position on the CMM can be found in *Figure 9*, and is expressed by

$$Z_{abs} = Z_{dro} - (Z_{nom} - Z_{lc}) \tag{2}$$

where Z_{abs} is the absolute position of the measured point with respect to the datum, Z_{dro} denotes the probe position on the CMM readout, Z_{nom} is the reference distance of the laser probe (a constant), and Z_{lc} depicts the reading of the laser probe. Here, we have to bear in mind that the capability of edge detection of the laser probe is only available for crossing the edge from a valid region to invalid region. Care must be taken to abide by this rule when planning the surface scanning path on the work surface, as shown in *Figure 10*.

Experimental results and CAD/CAM integration

The investigated laser probe emits a visible light spot, with wavelength 670 nm (red), in an elliptical shape of which the spot diameter changes from 110 to 140 μm within the measurement range. Its readings directly indicate the corresponding measured points on the work surface. In other words, with the implementation of the laser probe on the dimensional measurement, there is no need to work on the complicated probe radius compensation as required by normal touch-trigger probes, especially on the free-form surface profile measurements. *Figure 11* shows the measured results by the use of a laser probe and a touch-trigger probe separately on a flat surface. They are generally consistent with one another.

A master piece of free-form surface was initially fabricated in the laboratory through the normal mold-making procedure and painted red. Having previously been scanned by the automatic non-contact measurement system developed in this work, its surface data could be transferred to some CAD/CAM systems via proper DXF files. *Figure 12* shows the measured profile plotted by the SurfCAM package. Its corresponding NC codes of the cutter path were therefore generated, and the machining process was then carried out in a machining center to produce a copied part. This copied part was then sent back to the developed measurement system for proof inspection. The shape error of the copied part as compared with its master piece could then be obtained, as shown in *Figure 13* from which the maximum error was found within 30 μm. This amount is generally acceptable to the mold industry in the process of either sheet metal forming or plastic injection molding.

Concluding remarks

A non-contact type automatic measurement system was developed in this work for free-form surface profile measurements. The accuracy calibration of the laser probe was investigated with respect to various materials and the surface conditions of the workpiece. The surface red painting (or filming) technique and the edge detection technique were proposed to enhance measurement accuracy. A surface tracing method was employed for the automatic scanning process. This non-contact system could be applied to a CNC type CMM for automatic measurement, or a machining center for on-machine measurement. With the integration of commercially available CAD/CAM systems, the complete reverse engineering technique could further be achieved.

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