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# An autonomous multisensor in-situ metrology system for enabling high dynamic range freeform measurement capability of precision machine tools

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## Abstract

Meanwhile, in-situ measurement is of prime importance when trying to maintain the position of the workpiece for further compensation processes in order to improve the accuracy and efficiency of the precision machining of freeform surfaces. However, the coordinates of most of the machine tools with closed machine interfaces and control system are not accessible for users, which make it difficult to use the motion axes of the machine tool for in-situ measurement. This paper presents an autonomous multisensor in-situ metrology system for enabling the high dynamic range measurement capability of machine tools for freeform surfaces. It makes use of a designed tool path and an additional motion sensor to assist the registration of time-space data for the position estimation of a 2D laser scanner which measures the surface with a high lateral resolution and large area without the need to interface with the machine tool system. A prototype system was built and integrated into an ultra-precision polishing machine. Experimental results show that it measures freeform surfaces with high resolution, high repeatability, and large measurement range. The system not only improves the efficiency and accuracy of the precision machining process but also extends the capability of machine tools.

**Keywords:** freeform surface, in-situ metrology, multisensor, high dynamic range measurement, precision machining

## 1. Introduction

The Industrial 4.0 has imposed a great demand on in-situ and/or in-process production measurement in manufacturing environments. With the demand for ever higher-performance products, emphasis has been placed on the functional use of freeform surfaces in order to produce high-value-added products [1]. The trend towards product miniaturization further constitutes a driving force for the use of freeform surfaces in many fields, such as advanced optics [2] and biomedical applications [3], to improve the performance and provide versatile functionalities of the surfaces. This imposes new research challenges for high dynamic range measurement for freeform surfaces that can cover a larger scale with credible accuracy [4] and production measurement in manufacturing environments which demand high speed and robust in-situ and/or in-process surface measurement [5-8], especially when the workpiece is large and repositioning error is unacceptable. One reason is that with a large and heavy workpiece, it is difficult, sometimes impossible, to measure the workpiece with an off-line method. Another reason is that it is difficult to compensate the machining error if the workpiece is taken off for offline-line measurement and remounted on the machine tool. Moreover, most of the off-line measurement machines rely on one single sensor with a limited field of view which cannot provide a measurement result with a high dynamic range, which has a large measurement area and high resolution.

To address these challenges, one solution is to develop a separated metrology loop which does not rely on the structural loop of the machine tool. One of the examples is the Large Optics Diamond Turning Machine (LODTM) [9]. This method is similar to most of the modern metrology systems which move the sensor head with the moving linear or rotational stages. To enhance the measurement ability, different types of sensors can be chosen to mount on the moving axes. For instance, Lamb et al. [10] developed an automation system for industrial 3D laser digitizing which integrated the Hymarc Hyscan 45C laser scanner with a CMM machine which had a working volume of (2.0×1.3×1.0) m. The Hyscan 45C was built-in with a high power laser and a panning mirror which makes it capable for measuring steep walls and deep core out areas which is difficult to measure. Equipped with the products having advanced sensor technologies such as Gocator 3100 series which act as an area structured light sensor, the 3D surface data can be obtained in a single shot measurement with fast measurement speed and high accuracy [11]. However, integrating these sensors with a separated metrology frame is a complicated and expensive solution. Considering that the machine tools nowadays have precision advanced motion control, the motion accuracy is high and the motion error is within an acceptable accuracy range. Moreover, without machining force, the deformation and vibration situation is better compared with that in the machining process [12]. Installing a measurement system on the machine tool is one of the promising methods to implement in-situ measurement. With the large moving range of the motion axis of the machine tools, high dynamic range measurement can be achieved. Nowadays, there are commercial machine tools which provide in-situ metrology capability. The MIKRON HPM 600U/800U CNC machines provide an optional infrared touch probe which can be mounted on the machine replacing the tools to perform on-machine measurement [13]. Zeeko developed an on-machine stitching interferometer (OMSI) for mounting to a Zeeko IRP polishing machine to perform in-situ measurement [14]. However, they have to be implemented by the machine tool manufacturers since it is necessary to access the coordinate information from the CNC controller.

Since most of the motion control interfaces of the machine tools are not open to the users and researchers, it is difficult to obtain the coordinate information of the motion axis and further develop it on the machine tool for in-situ measurement. This issue also exists in the methods which integrate additional sensors into the metrology systems with motion stages. Without the coordinate information of the axes, it is difficult to combine the sensor data to obtain a holistic measurement result. Without directly accessing the coordinate information of the machines, the position of the sensor has to be estimated. Position estimation is widely used in robots. Kiyoshi and Eimei [15] used an optical fibre gyroscope to estimate the position of mobile robot. However, the position estimation error was large. Latt et al. [16] developed a drift-free position estimation method using inertial sensors for periodic or quasi-periodic motion. The method combined linear filtering stage with adaptive filtering stage to remove drift and attenuation. The root mean square (RMS) error of the proposed method was about 3 μm while the maximum error was 8.9 μm. However, the prior knowledge of the motion was needed in this method. In order to address this issue, this paper presents a method to estimate the position of the motion axis with an additional motion sensor when the motion is controlled with a designed trajectory. With the help of a 2D laser scanner and an additional motion sensor, a multisensor in-situ metrology system mounted on the machine tool was built and demonstrated for the high dynamic range measurement of a freeform surface. Together with the information provided by the designed trajectory, the position estimation accuracy is significantly enhanced as compared with the methods solely based on the motion sensor. The methodology and experimental setup details are described and the measurement result and its associated uncertainty are also analyzed. The successful establishment of this method provides a new way for in-situ high dynamic range measurement for freeform surfaces.

## 2. Multisensor in-situ metrology system

Fig. 1 shows a schematic diagram of the multisensor in-situ metrology (MIM) system. Without the need to build an independent metrology frame, instead, the system is built and attached to the motion axis of the machine tool as a sensor module incorporated in a specially designed fixture. The sensor module contains two types of sensors, which includes a 2D laser scanner as a geometrical sensor and a motion sensor. The sensor module is mounted on the machine tool and scans along the surface of the workpiece with a purposely designed tool path. During the scanning of the surfaces, the data from the laser scanner and the motion sensor is simultaneously acquired by a computer system. After data processing, the coordinate information of the sensor module is determined by integrating the designed tool path and the motion sensor data. The whole surface can be reconstructed by the coordinate information of the sensor module and the laser scanner data. The MIM system is mechanically attached to the machine tool. However, it is relatively independent of the machine tool since it has no direct electrical connection to the control system of the machine tool. The independent feature of the MIM system extends its applications to a large field in the industries. This is a very useful attribute of the MIM system.

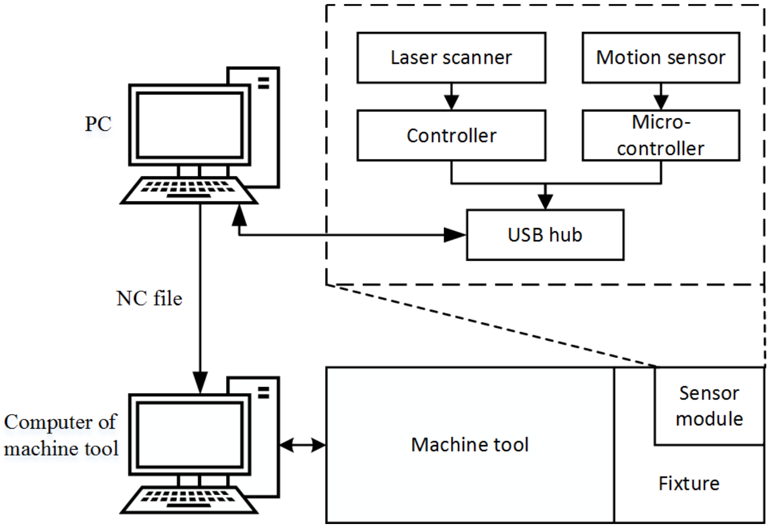

**Figure 1.** Diagram of the multisensor in-situ metrology system

A prototype of the MIM system was designed for a multi-axis ultra-precision polishing machine with 3 linear axes (X, Y, Z), 3 rotational axes (A, B, C) and a spindle axis (H). The configuration of the motion axes is shown in Fig. 2. With a purposely designed precision fixture, the sensor module is mounted on the B axis without removing the polishing head while the workpiece is mounted on the C axis. With this setup, the sensor module can be moved along the A and B axes and the workpiece can be moved along the X, Y, Z and C axes. This setup realizes a large scanning volume for the sensor module which enables the system for large range measurement.

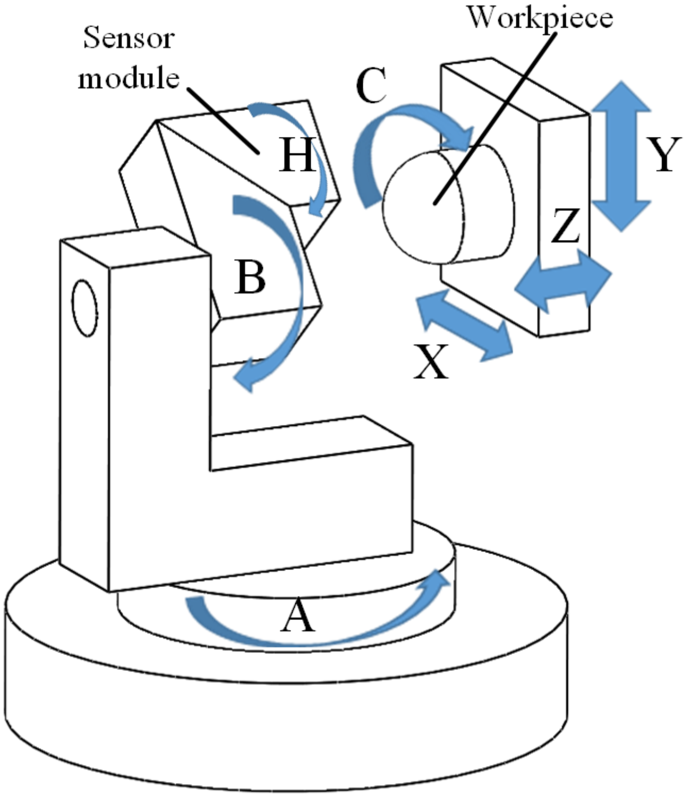

**Figure 2.** Motion axes setup of the MIM system mounted on the multi-axis ultra-precision polishing machine. The sensor module is mounted on the B axis covering H axis while the workpiece is mounted on the C axis.

Fig. 3 shows the scanning strategy of the MIM system. The scanning strategy consists of rotational motion of the B axis and linear motions of the X axis, Y axis, and Z axis. The A axis has a fixed angle to ensure that the laser scanner is perpendicular to the X-Y plane. The laser scanner is rotated around the B axis and a scanning slice can be generated, as shown in the highlighted zone in Fig. 3. The workpiece is moved along the X axis, Y axis and Z axis, combined with the scanning of the B axis. As a result, the whole surface of the workpiece can be scanned. The total scanning area is large as this is determined by the moving range of the motion axis of the machine tool. The resolution of the scanning is high with the help of the high sampling rate of the laser scanner and the motion sensor as well as a fine feedrate. On the other hand, the measurement range is limited by the moving range of the motion axes while the measurement resolution is limited by the laser scanner and the sampling rate. This is different from that of single CCD camera measurement systems in which the measurement range and resolution need to be compromised. In other words, the MIM system can achieve a large measurement range with high resolution. This is the principle of the high dynamic range measurement of the MIM system.

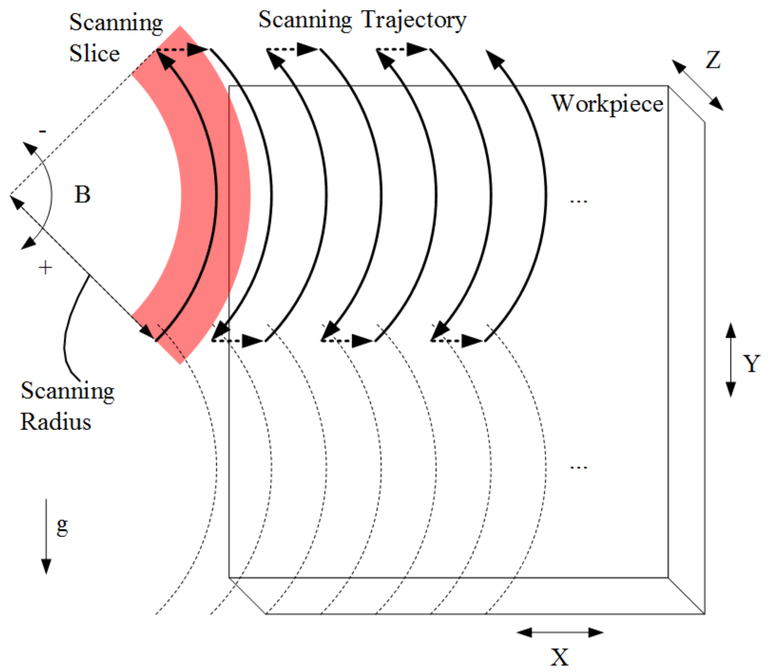

**Figure 3.** Scanning strategy of the metrology system

The motion sensor consists of a 3-axis acceleration sensor and a 3-axis gyroscope. While scanning by the proposed method, the gyroscope data along the Z direction and the acceleration data in the Y (also g) direction are used to assist of the determination of the positon for each dataset, together with the designed trajectory. Since the data from the laser scanner and the motion sensor is obtained simultaneously, with the designed scanning angle for the B axis, the coordinate information for each line of the laser scanner can be determined accordingly. The coordinate of the sensor module is determined by the time signal combining with the space signal from the design trajectory. With coordinate transformation for the scanning lines, the whole surface can be reconstructed as a point cloud format incorporating both a large area and a high resolution. To avoid the missing of data and to provide the stitching ability for future work, the scanning slices are designed to be overlapped.

## 3. Experimental setup and procedures

The experiment was conducted on an IRP200 7-axis polishing machine from Zeeko Co. Ltd., UK. The experimental setup is shown in Fig. 4. The sensor module consists of a Keyence LJ-G015 2D laser sensor, a MPU-6050 motion sensor (6-axis Motion Tracking device) and an Arduino UNO with Atmel ATmega16 micro-controller and it is mounted on the B axis via a purposely-designed fixture and the workpiece is mounted on the C axis of the polishing machine. As shown in Fig. 5, the fixture is designed as two separated parts. The first part is attached to the H axis while the second part is detachable and adjustable around the H axis for alignment adjustment purposes. The laser sensor measures a 2D profile with an 8 mm length, a 10 µm pitch and a 5.2 mm Z axis measurement range. The laser sensor is connected to a Keyence LJ-G5000 laser controller and the motion sensor is connected to the micro-controller. Both the laser controller and the micro-controller are connected to a laptop computer via a USB hub. The laptop computer communicates with the laser controller via a VB.Net library and controls the micro-controller via a purposely-developed USB-serial protocol by the authors. The baud rate is set to 230400 bps. The specifications of the motion sensor and the 2D laser sensor are shown in Table 1.

**Table 1**

Specifications of the motion sensor and the 2D laser sensor

| **Motion sensor (InvenSense MPU-6050)** | |
|---|---|
| Gyroscope full-scale range | ±250°/sec |
| Accelerometer full-scale range | ±2*g* |
| Analog-to-digital converters word length | 16 bits |
| **2D laser sensor (Keyence LJ-G015)** | |
| Z-axis measuring range | ±2.3 mm |

| | |
|---|---|
| X-axis measuring range (reference distance) | 7.0 mm |
| Z-axis repeatability | 0.2 μm |
| X-axis repeatability | 2.5 μm |

The embedded software for the micro-controller is written in C computing language and the software on the laptop is written in VB.Net programming language, integrated with the application program interface (API) for the laser controller. The data from the laser sensor and motion sensor is obtained simultaneously and recorded as a data file for data processing. The recorded time for every dataset is also retained with millisecond accuracy. The data processing is implemented by Matlab programming language.

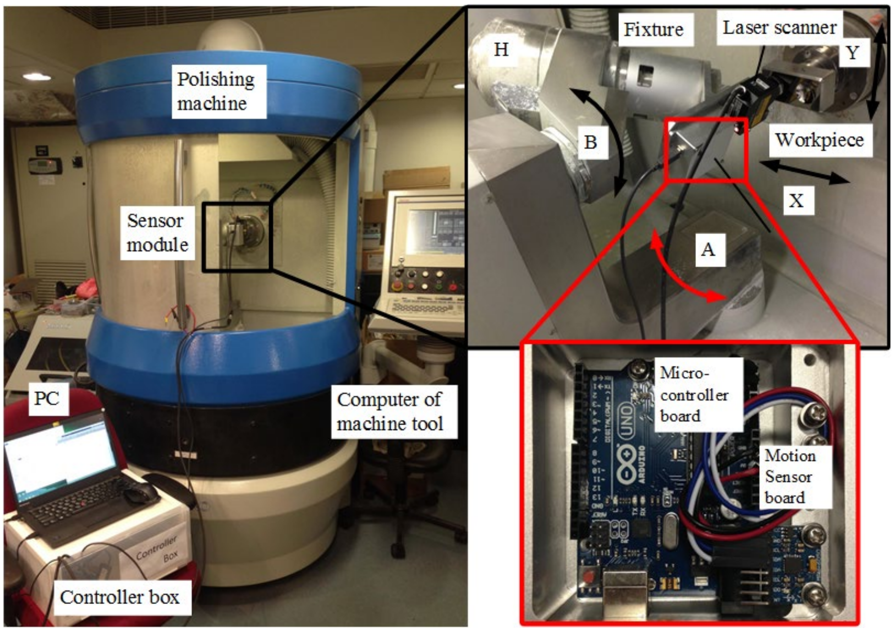

**Figure 4.** Experimental setup of the metrology system on the multi-axis machine tool

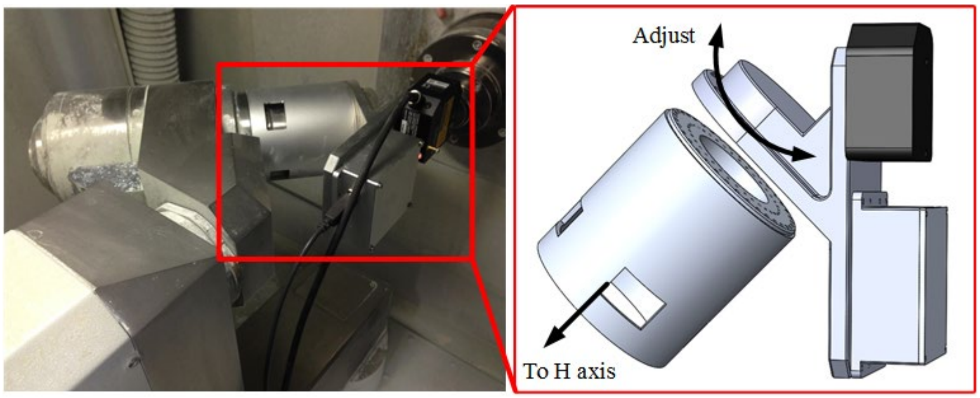

**Figure. 5.** Sensor module and fixture

A contrived freeform workpiece was purposely-designed and manufactured for evaluation of the developed multisensor in-situ metrology system. Fig. 6 shows the drawing of the contrived freeform workpiece which is designed based on the concept of the Modular Freeform Gauges (MFG) for ease of calibration [17]. The dimension of the surface of the workpiece is 100 mm × 50 mm and the height is 5 mm. The process to conduct in-situ measurement for the designed MIM system starts with the installation of the sensor module and the fixture on the machine. The next step is alignment adjustment to minimize the installation error of the sensor module. The scanning parameters are then determined and the NC tool path file is generated. Hence, data acquisition and data processing are finally undertaken.

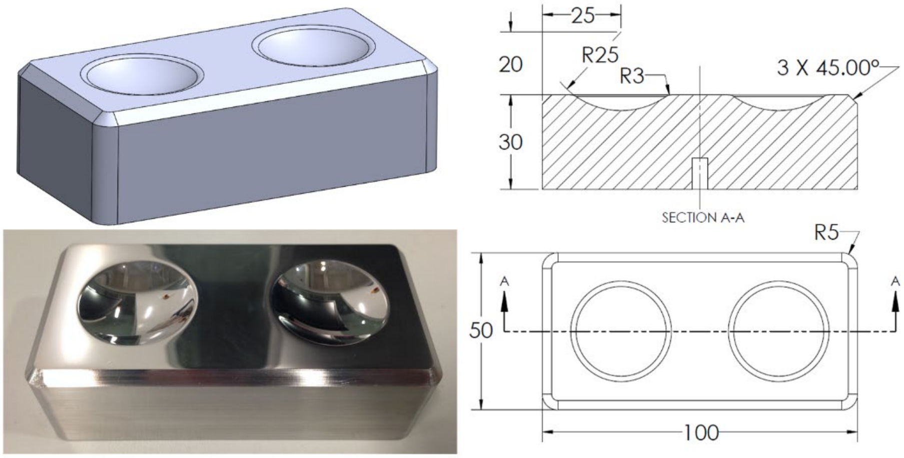

**Figure. 6.** Designed freeform workpiece

### *3.1. Alignment adjustment for the sensor module*

With the designed fixture installed on the polishing machine, there are two alignments to be adjusted. One is the perpendicularity of the laser scanner to the X-Y plane, which is determined by the angle of the A axis. The other alignment is the parallelism of the laser scanner to the X-Z plane which is determined by the angle of adjustment, as shown in Fig. 5.

To fine-tune the perpendicularity of the laser scanner to the X-Y plane, a flat surface was mounted on the C axis and the profile of the flat surface was measured while adjusting the angle of the A axis. A best-fit line was generated, to the measurement data by using the least square method and the best position was determined by minimizing the tilting angle of the line. To adjust the parallelism of the laser scanner to the X-Z plane, a standard sphere was mounted on the C axis and the profile was measured while fine-tuning the angle of the fixture. A circle was fitted for the measured data and the radius of the circle was calculated. The best position was determined by maximizing the radius through adjusting the fixture.

After the alignment adjustment, the scanning radius of the slice was determined and is expressed by Eq. (1).

$$R_s = |X_s| - (\frac{1}{2}L - C_x) \tag{1}$$

where $X_s$ is the X coordinate of the standard sphere, $L$ is the measurement length of the 2D laser scanner, and $C_x$ is the X coordinate of the center for the fitted circle.

### *3.2. Determination of the scanning parameters*

For every measurement, the scanning parameters should be optimized to be able to cover the whole measured surface by having the right balance between the scanning speed and the data resolution. For the freeform workpiece shown in Fig. 6, the scanning parameters are shown in Table 2. It is noted that the scanning with the B axis and X axis is good enough for this workpiece since the scanning range can cover the whole workpiece. After the scanning parameters were determined, the tool path was generated by using the G-code as the NC file for the polishing machine.

### *3.3. Data acquisition*

The NC file for the scanning trajectory (see Fig. 3) was implemented on the polishing machine and the data acquisition was undertaken. The data acquisition process was controlled by the software in the laptop computer as a timer loop (15 ms). For every cycle, a command is issued by the laptop computer to the micro-controller to obtain the motion sensor data and the function is then called to receive the data from the laser scanner through the application program interface (API). The data of the laser scanner, the data of the motion sensor, and the captured time signal (in milliseconds) were stored in a text file for data processing. The time signal was recorded to solve the jitter issue in the data acquisition process.

**Table 2**

**Scanning parameters**

| | |
|---|---|
| B axis range | 25° ~ -25° |
| X axis pitch | 5 mm |
| Feedrate | 20 mm/min |
| Scanning Radius | 73.475 mm |

### *3.4. Data processing*

The data processing was done by the data processing module which is written in Matlab programing language. The first data to be analyzed was the motion data. Since the B axis was rotating around the Z axis, the most significant motion data is the acceleration data of the Y axis and gyroscope data of the Z axis. The raw data was first normalized with zero mean and filtered for further processing. To avoid a phase shift in filtering which significantly affects the accuracy, a forward-backward filtering algorithm [18] was used to filter the raw data. The normalized raw data and the filtered data of the acceleration and gyroscope are shown in Fig. 7.

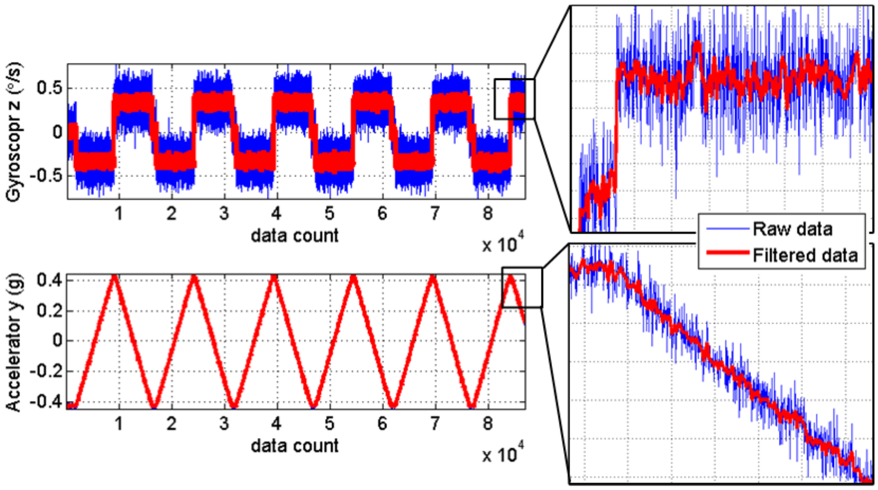

**Figure 7.** Raw data and filtered data

Since the motion was slow, the effect of the acceleration and deceleration was insignificant. In this study, the scanning slices were determined by setting two thresholds in the filtered gyroscope data for the anti-clockwise scanning and clockwise scanning, respectively. It is interesting to note that there was jitter in the data capturing process, which means that the capturing time was not evenly distributed. To address this issue, the datasets within one slice and their associated scanning angle were calculated according to the actual capturing time, which is determined by Eq. (2).

$$a_i = a_0 + \frac{t_i - t_0}{t_T} a_r \tag{2}$$

where $a_0$ is the start angle, $t_0$ is the start time, $t_i$ is the capturing time for the $i$th dataset, $t_T$ is the total time, and $a_r$ is the angle of the scanning range.

After the angles for every dataset were identified, the coordinate information associated with the data from the laser scanner can be determined by the transformation matrices and the transformed scanned data can be determined by Eq. (3)

$$S_t = M_{R_z} M_{T_x} S_m \tag{3}$$

where $S_m$ is original measurement data with X and Z coordinate data from the 2D laser scanner and the Y coordinate is set to zeros, $M_{T_x}$ is the transformation matrix to translate the data according to the scanning radius, and $M_{R_z}$ is the transformation matrix to rotate the data according to the determined scanning angle.

## 4. Results and discussion

The measurement data was acquired in a point cloud format and the number of points for the designed workpiece was about 75 million, which indicates that there were about 15,000 points per mm$^2$. With a higher sampling rate, the resolution can be increased. The scanning time was about 60 minutes for a surface of 100 mm × 50 mm and the processing time was about 3 minutes. With the use of a faster microprocessor to increase the sampling rate, the feedrate can be increased and the scanning time can be shortened. To visualize the result, the measurement data was down-sampled and the result is shown in Fig. 8. It is interesting to note that there is some measurement noise near the lower part of the spherical area, which is caused by the reflection of the laser light. The reflection area can be determined by the geometry of the surface and the angle of the laser beam. To address this issue, rotating the A axis or C axis for some specific area may be implemented in future work.

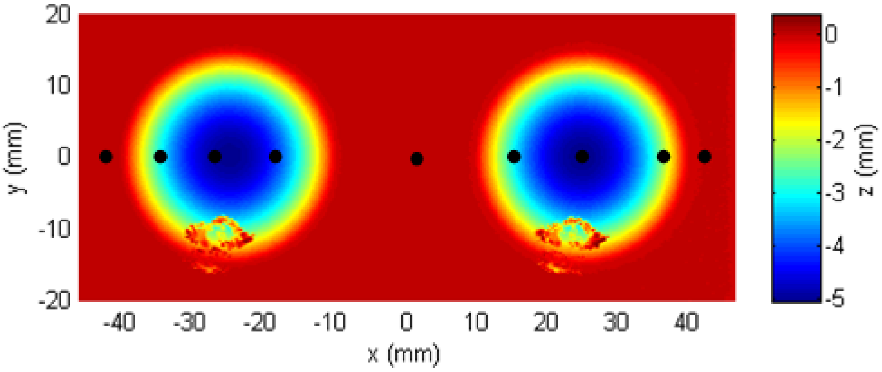

**Figure 8.** Scanned freeform surface

The measurement result was compared with the result measured by a Werth Coordinate Measuring Machine (CMM) (Video Check UA 400) with a touch probe TP200 (Renishaw UK). Since the measurement accuracy of the CMM is high with Maximum Permissible Measuring Error (MPE) of (0.75+L/300) µm at a temperature range of 20°C±2K and humidity of 50±5%, the probing error is as low as ±0.65 µm for the trigger probe, the measurement result of the CMM was used as a reference. The measurement result of the proposed system was registered to that of the CMM by using an iterative closest point (ICP) method [19]. The registration result is shown in Fig. 9. The result shows that the two datasets are well registered.

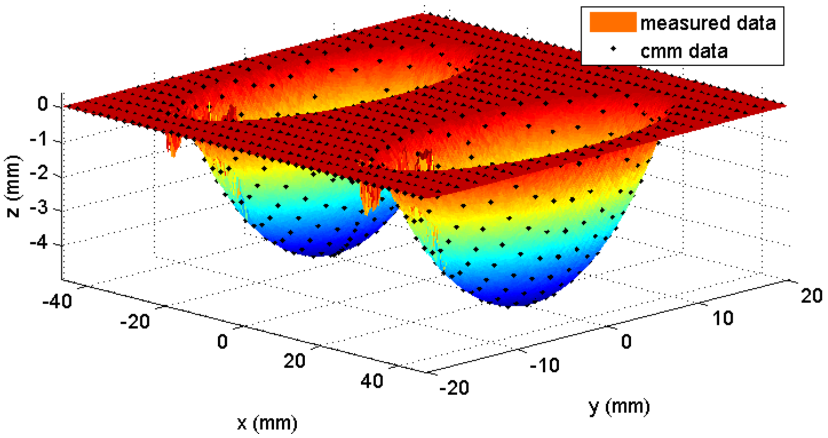

**Figure 9.** Registration result for the MIM measurement data and the CMM measurement data

The measurement result of the MIM system was evaluated at nine selected representative positions along the center line of the surface as shown in Fig. 8. The sample positions cover the flat and the tilted surfaces. Five repeated measurements were conducted. As shown in Fig. 10, the results were compared with the measured data by the CMM after registration. The error bar depicts the standard deviation of the repeated measurements. The result shows that measurement data at the flat surface had higher accuracy than that at the tilted surface, i.e. 5 μm compared to 10 μm from the reference CMM data, while the repeatability at every selected position was about ±4 μm. The uncertainty of the measurement may be due to the imperfection of the fixture, alignment error of the laser sensor, the motion error, and vibration of the machine tool. The measurement range divided by the measurement uncertainty is about 500:1 and this is believed to be able to be enhanced to 1000:1 by designing and fabricating a higher accurate fixture, the use of a higher-speed micro-controller and the incorporation of a data stitching method in future work. Also, a higher accurate laser scanner can be used to enhance the accuracy of the MIM system.

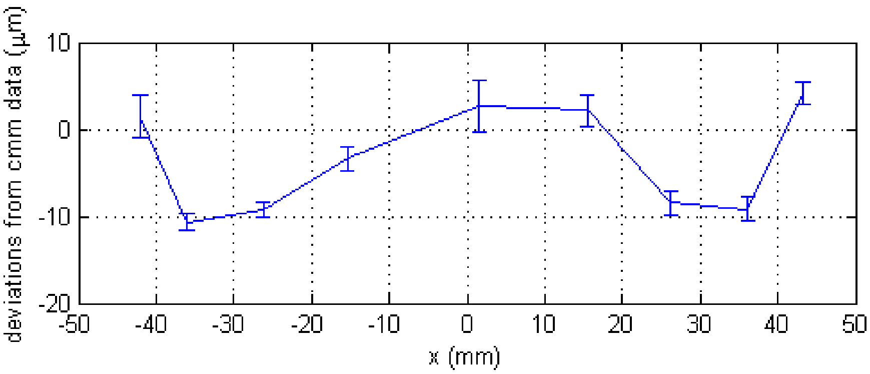

**Figure 10.** Performance evaluation result

## 5. Conclusion

In this paper, an autonomous multisensor in-situ measurement system has been developed which attempts to enable the precision machine tools to perform high dynamic range measurement of freeform surfaces. This system makes use of a motion sensor to assist the estimation of the position for a 2D laser scanner while it is scanning with a purposely designed trajectory. Without interfacing with the motion controller of the machine tool, this system has very high feasibility and it can be easily integrated into different machine tools. The result shows that the method is not only suitable for in-situ measurement but also provides high dynamic range measurement result with large measurement area and high resolution. The measurement uncertainty of the system is in the order of 10 micrometres. Future work will be undertaken to further enhance the performance of the system and test the system on more machine tools.

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