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Article

Length Distortions of a Spindle Under the Influences of Temperatures Rising Duration Machining and Compensation Solution

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Abstract: Facing with errors of a product after machining was a big title in this field. That will affect to product's quality with unpredictable situation when products is in use for some particular application such as in medical facilities. Improving the precision of machine tools by exploring temperature on multiple points and measuring differential locations of the spindle is going to be executed in this study. A temperature measurement tool and a software running on Windows platform have been developed and combining with Non-bar system in order to support analyzing the temperature rising with the changes of length of the spindle to find the compensation solution based on eccentricity and length distortion. In this study, the whole tests have done on UX300 five – axis CNC machine tools for this investigation and the errors after applying compensation function have reduced 70% at least, with respect to the errors after machining without using compensation function.

Keywords: length compensation; non-bar system; machine tools.

1. Introduction

Computer Numerical Control (CNC) machines are a vital part of today's manufacturing industries. CNC machines were able to be controlled by programming language to carry out a wider variety of tasks with greater accuracy. These machines also allow for a more automated control, which improves productivity. CNC machine operators work in a wide variety of fields.

Due to the high precision involved, in some particular fields require a high accuracy. CNC machines are typically employed in order to ensure the finished product meets exact dimensions. But still there, an error is always existed, the roughness of work-pieces describes the quality of product. Thus, this investigation has led to a process and data analyses for decreasing error. Improving the precision of product after machining is very difficult. Because there are various reasons that could affected to the process such as temperature, vibration and pressure. In additional, each of the factors may provide a non-linear data. Otherwise, the geometric error of the machine tool is attributed to the inaccuracy of the machine tool and the cutter.

The cutting force-induced error is the dominant error source when turning small work-pieces or in hard turning. A real-time error compensation system has developed on a CNC turning centre by using an independent computer controller Yang et al. [1]. Kops et al. [2] provided a formula to correlate the detection and the depth of cut but that only considered the radial component of cutting force. A model was proposed for bar turning that included all cutting force components by Phan et al. [3], but the model was rather complicated.

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An artificial neural network was applied for estimating the thermal errors as a distribution by Veldhuis et al. [4]. The spindle thermal drift is the dominant source of thermal-induced errors such as Bryan [5].

In this investigation, the data analyses, simulations and experiments all are executed based on the changes of temperature and spindle configurations. Simultaneous measurement methods proposed by Chen et al. and Murakami et al. [6,7] are needed in collecting data with fast response and high reliability. The miniaturization of error after machining has implemented Non-bar system. Non-bar system was an optical calibration system with no linkage bar, consisting of a master detector module, a ball lens module and a signal module. Non-bar system measures the total error of multiple axes movement simultaneously [9-15] and the installation is quite easy. Compensation method is produced by Yuan et al. [8], which is a real-time compensation technique.

The workpiece after experiment in this study is verify by using a three-dimensional measuring instrument ABLE-686-CNC provided by Jingsh Meng Technology Co. Ltd., Taichung city, Taiwan.

2. System

The system was built with combination of temperature measurement tool and Non-bar system that allows us to measure temperatures on multiple points and the locations of spindle under the influence of temperature, respectively. The samples of temperature and the displacement of z axis under the effects of temperature changes are measured and read from sensors, simultaneously, to ensure no data distortion. Because, if the data have collected asynchronously, that will affect to results significantly and causes unexpected errors, thus, the locations from non-bar system and temperatures from sensors need to be synchronous.

In this research, the UX300 five-axis CNC machine (UX300, Quaser Machine Tools Inc., Taichung, Taiwan) running HEIDENHAIN PLC (Programmable Logic Controller) is used for experiments. The foregoing system is consisted of a temperature measurement tool and non-bar system as inputs, a computer running Windows Operating System as the processor, HEIDENHAIN PLC as outputs. Wi-Fi connection and Ethernet connection are required as communication methods.

The temperature measurement tool is actually a subsystem that includes many temperature sensors connected together in series and a controller. And, the non-bar system is going to be used to determine location of target. The processor is to computing the compensation value based on inputs (temperatures and locations) by following a provided function, which are mathematical equations.

The terminal of collected data is a computer and those data are going to be handled by a software. After data analysis and calculation, then get length compensation equation with parameters relative to the temperature. The value computed by a program in a computer is going to be transferred to five - axis CNC machine tool via Ethernet cable.

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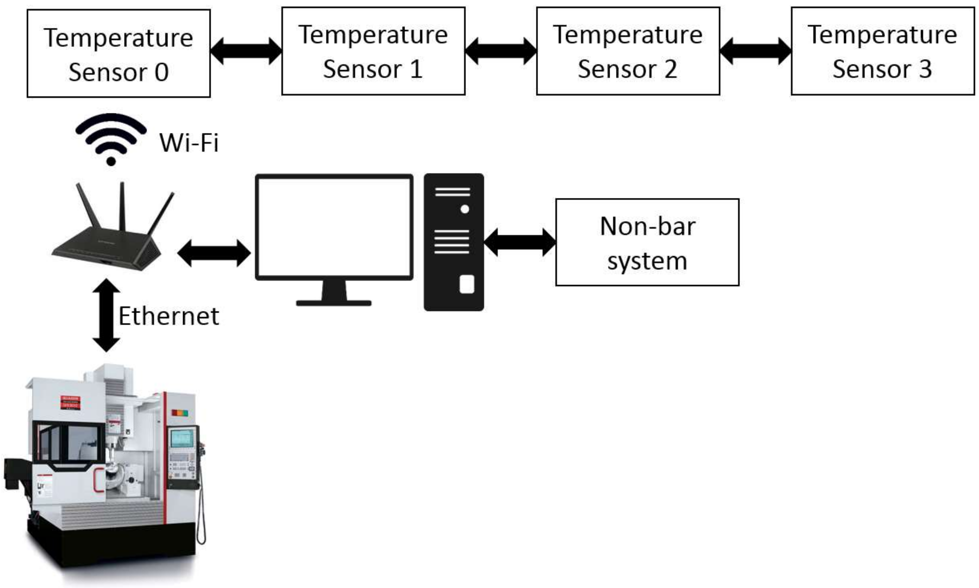

Figure 1. The System

2.1. Temperature measurement tool

The traditional temperature measurement system provides multiple sensors connected to controller, then between each of sensors and controller will exist wires to connect them together as shown in Figure 2. Because temperature sensors will be attached on spindle during machining time. That will be unsafe to allow many wires placing close to spindle when machine is actually processing workpieces. Furthermore, quantity of sensors is limited by connection pins on selected controller.

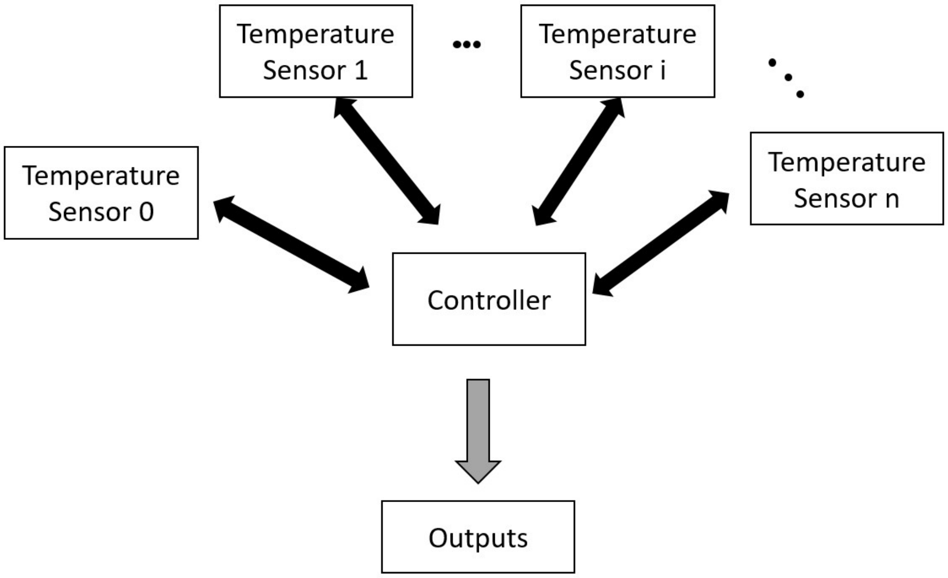

Figure 2. Traditional System

In this section, the traditional system will be replaced by a new system as shown in Figure 3. By using a communication protocol was called 1-Wire that designed by Dallas Semiconductor Corporation. Then, the controller only needs to connect to the first sensor, the second sensor will connect to the first sensor, other sensors will be connected in series with available connection of the last sensor in the system instead of connecting each of sensors to the controller in parallel. Other advantage of this method is no limited quantity of sensors in the system and easier to install.

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The DS18B20 temperature sensors have been used for this research with selectable resolutions of 0.5 (°C), 0.25 (°C), 0.125 (°C) and 0.0625 (°C) and the highest resolution (0.0625°C) was selected in this study for more sensitive, the sensors measure temperatures from -55°C to +125°C (-67°F to +257°F). The Figure 4 shows components of the system, (a) shows a temperature sensor. In the (b), where s is a DS18B20 temperature sensor and m is a magnet for attaching sensor on the spindle. The whole sensors are shown in Figure 4 (c) and the controller is shown in Figure 4 (d).

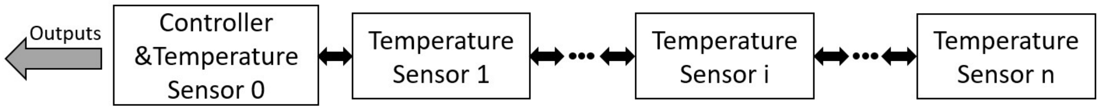
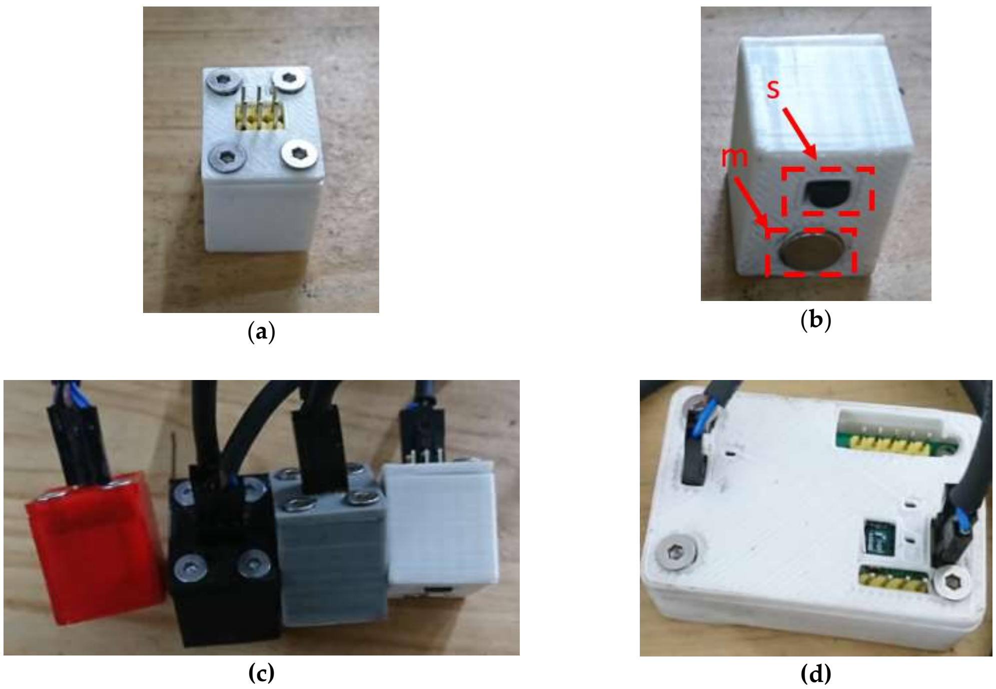
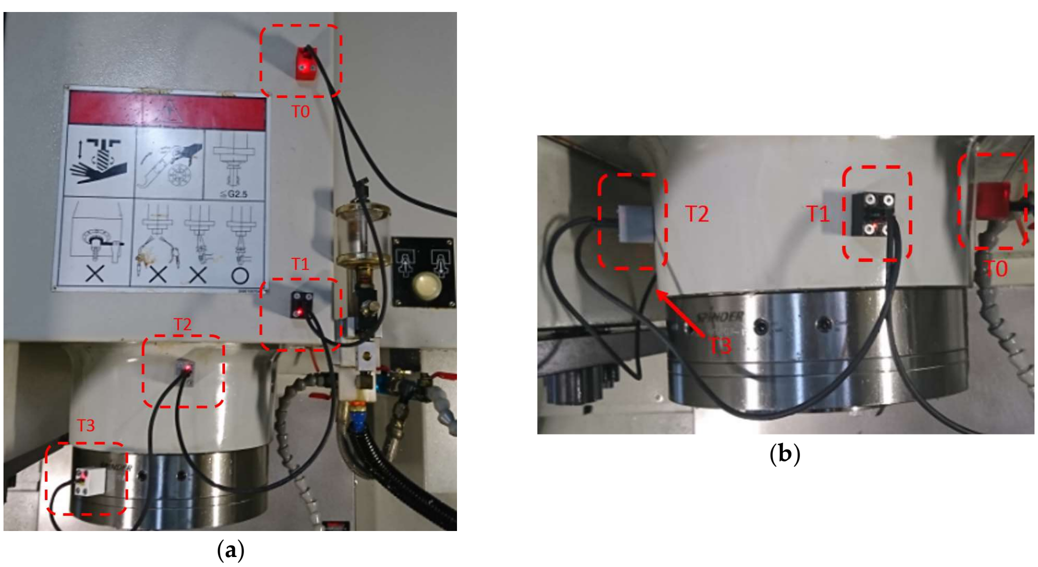


Figure 3. One-Wire System



(**a**) (**b**) (**c**) (**d**)

Figure 4. Temperature Sensor Tool. (a) DS18B20 Temperature; (b) DS18B20 Temperature's down-side; (c) Four DS18B20 temperatures; (d) the controller.



(**a**) (**b**)

Figure 5. Arrangements of temperature sensors on the spindle. (a) Type one; (b) Type two.

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The DS18B20 temperature sensors will be configured by a micro-controller (Nano102, Nuvoton Technology Corp., Hsinchu, Taiwan) - The 32-bit microcontroller embedded with ARM Cortex M0 core running 12MHz frequency. The system has been integrated with a Wi-Fi chip allowing wireless data acquisition and transmission system executed. The tool is coded to connect to an available router and the connection between the tool and the computer is established.

In this investigation, there are four points that have explored on, for temperatures. The temperature sensors will be installed on the spindle as shown in Figure 5, where “T0”, “T1”, “T2” and “T3” are the four sensors.

The sensors will be changed in various types of arrangement as Figure 5-a and Figure 5-b. Because, the each sensor arrangement may affect to measured temperatures. But after doing experiments, the effects of sensor arrangements have changed by an insignificant amount.

2.2. System Configuration

This section will declare components those need to prepare for collecting data and experiments by taking advantage of Non-Bar system.

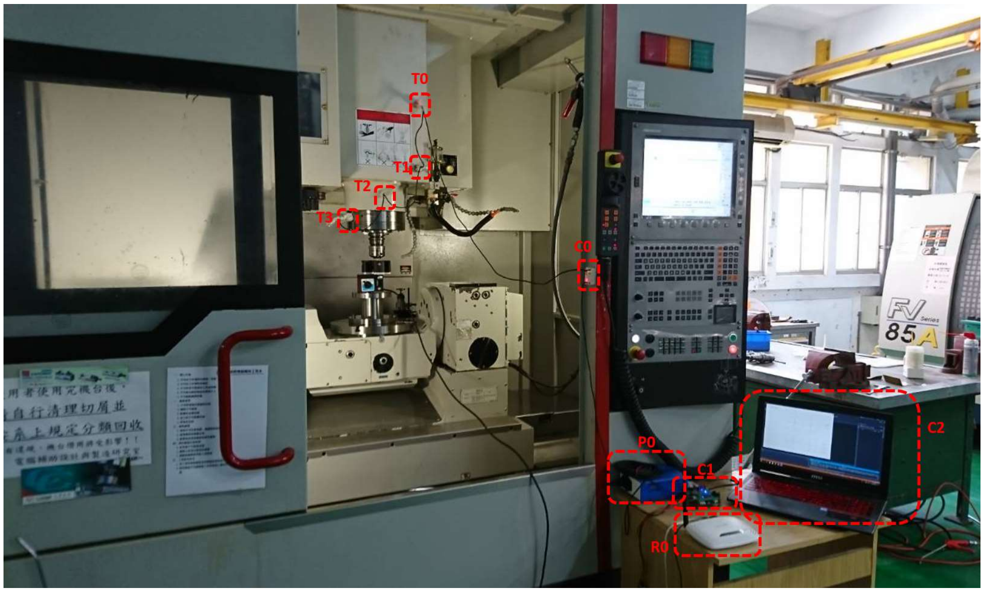

Figure 6. Measurement system

The Figure 6 shows the whole system for sampling and data collections, where T0, T1, T2 and T3 are temperature sensors, the C0 is temperature controller integrated Wi-Fi, it can transfer and receive data via Wi-Fi, the P0 is power supply for C0 and non-bar system, the C1 is non-bar system controller that will connect to a computer and transfer data via USB communication. The Non-bar system has used for simulating the cutter and by that way, the displacement of z axis could be evaluated and transferred to a computer. The C2 is a laptop running Windows Operating System, which has used as mentioned processor for this study. The R0 is a Wi-Fi router working as Access Point (AP) mode, C0 and computer C2 will scan Wi-Fi’s Service Set Identifiers (SSID) around them and connect to R0’s SSID. The CNC machine has to connect to R0 as well through Ethernet cable.

Once compensation functions are ready for experiments, then the non-bar system needs to be removed. Now, an actual cutter will be used instead of non-bar system and the compensation process will be executed.

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3. Sampling and Data Analyses

The sampling is very important, that will give us a view of temperature changes and the changes of spindle's height. The implementation of sampling is arranged as shown in Figure 7 including temperature sensors, the Non-bar system and a computer. This process will take eight hours, the whole data will be stored and plotted on user interface of software. During sampling time, whole temperature data will be transferred via WIFI to computer and Non-bar will transfer displacement of spindle through USB 2.0 cable to computer.

Figure 7. Arrangement of system

The Figure 8 shows the whole process in this investigation. First configurations are eight hours process and speed of spindle of 9000 rpm, every minute will read values of temperatures. After we finish sampling, the data analysis and calculations will be deployed for finding out the compensation solution, each solution will be tested by simulating with two cases, one without using compensation equation and one with implementing compensation equation, then, the comparisons of two cases are executed. The "Error0" "Error1" "Error2" "Error3" where the errors of the spindle are, wish these errors as small as possible. In this study, we plan the error after using compensation will be decreased at least a half of the original error without using compensation function. If the simulation has a good result, the process will go for next step with experiment upon work-pieces, after that, the same step, the comparison will be executed again. If the result is failed, the samples will be considered and sampling will be deployed if needed.

The error affect to z axis mostly, this study focuses on z axis and does the compensation on z axis only.

Under the influences of temperatures, the shape of spindle will be distorted in various shapes as shown in Figure 9. Alternatively, the effects of deformation will decrease the precision of the machine.

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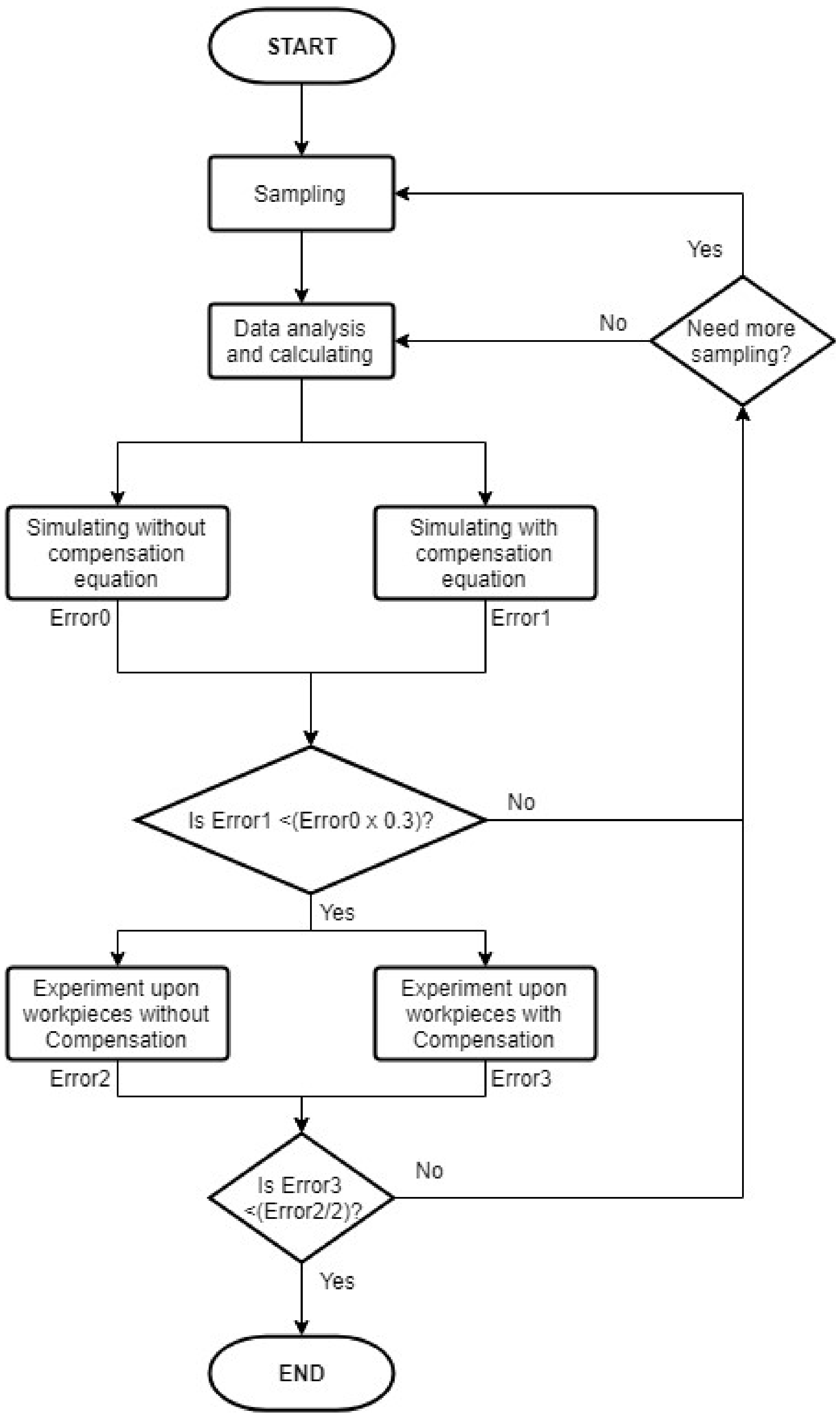

Figure 8. The Process

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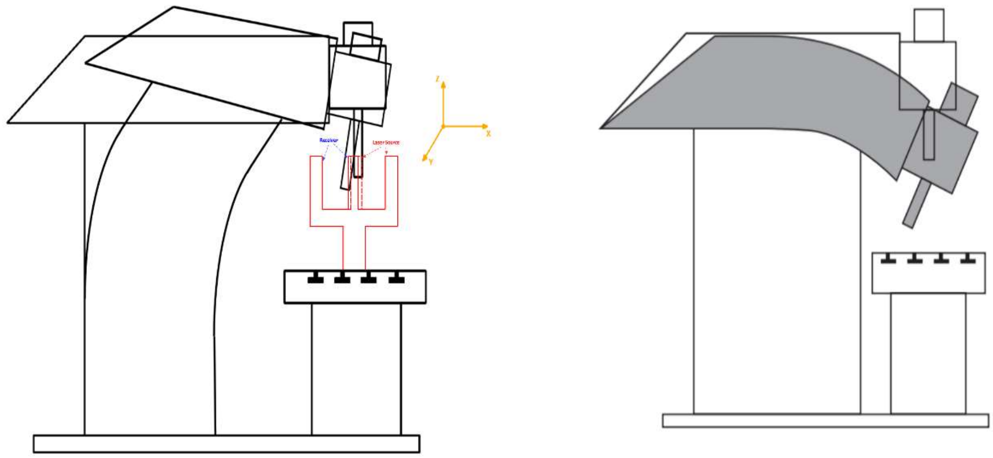

(**a**) (**b**)

Figure 9. Deformations of spindle

The data collection process is deployed, with the speed of spindle is set to 9000 rpm, every minute will read values of temperatures and the each experiment is processed for eight hours.

The temperatures is evaluated by Equation (1), where T_1, T_2, T_3 and T_4 are four points explored temperatures. The result of Equation (1) is an average of temperatures. These computations are executed by the frequency of 1/60 Hz.

$$T_{avr} = \frac{T_1 + T_2 + T_3 + T_4}{4} \tag{1}$$

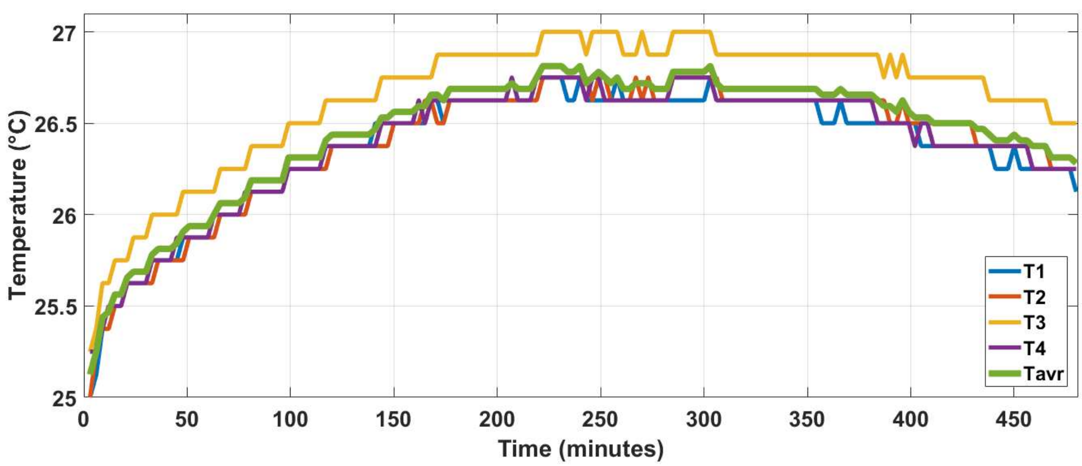

Figure 10. Temperatures

We have collected temperatures for three months and one of the results is shown in Figure 10 with data of four temperature sensors and average of temperatures for eight hours, to make sure that the changes of temperature are enough in our scope, not the range. Because, it will be difficult to manage the ranges of temperatures in eight hours for every day. To make it more clearly, the temperatures start from 25.2 °C and rising to 27 °C for this time, but next time, the starting point may not be 25.2 °C and ending point may not be 27 °C either, we know the temperature changing every day. Consequently, bringing the values of temperatures to compensating after collections is not feasible. In this investigation, we are using differential temperatures to create compensation equations. Assuming that the equation of differential temperature is formed as Equation (2),

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$$f_{T(a)} = A_1a^6 + A_2a^5 + A_3a^4 + A_4a^3 + A_5a^2 + A_6a + A_7 \tag{2}$$

where a is a variable of differential temperature. The A_1, A_2 ,…, A_7 are coefficients of the equation. The Equation (2) can be rewritten as Equation (3) in matrix form. The $[f_{T(a)}]$ is obtained from the collected data. Then, the results of Equation (3) will give us the equation of temperature that will be used to compensate for the effects of temperature.

$$\begin{bmatrix} a_0^6 & a_0^5 & a_0^4 & a_0^3 & a_0^2 & a_0^1 & a_0^0 \\ a_1^6 & a_1^5 & a_1^4 & a_1^3 & a_1^2 & a_1^1 & a_1^0 \\ a_2^6 & a_2^5 & a_2^4 & a_2^3 & a_2^2 & a_2^1 & a_2^0 \\ a_3^6 & a_3^5 & a_3^4 & a_3^3 & a_3^2 & a_3^1 & a_3^0 \\ a_4^6 & a_4^5 & a_4^4 & a_4^3 & a_4^2 & a_4^1 & a_4^0 \\ a_5^6 & a_5^5 & a_5^4 & a_5^3 & a_5^2 & a_5^1 & a_5^0 \\ a_6^6 & a_6^5 & a_6^4 & a_6^3 & a_6^2 & a_6^1 & a_6^0 \end{bmatrix} + \begin{bmatrix} A_1 \\ A_2 \\ A_3 \\ A_4 \\ A_5 \\ A_6 \\ A_7 \end{bmatrix} = \left[f_{T(a)} \right] \tag{3}$$

Obviously, the compensation will not be completed with only differential temperature factor. There might be another factor. Assuming that there is $B(b)$ factor with variable b shown in Equation (4). The spindle turning will generate forces such as centrifugal force, these forces will affect and push deformation of spindle occurring faster.

$$F_{compen.(a,b)} = f(a) + B(b) \tag{4}$$

Now, we are going to find the factor B. Because, when spindle starts to spin, we will always get an offset as shown in Figure 11. Considering Figure 12, assuming we know the convergent point of the sphere in non-bar system. It is easy to recognize that the d_2 is shorter than the d_1, but d_1 is actual length and d_2 is the measured length.

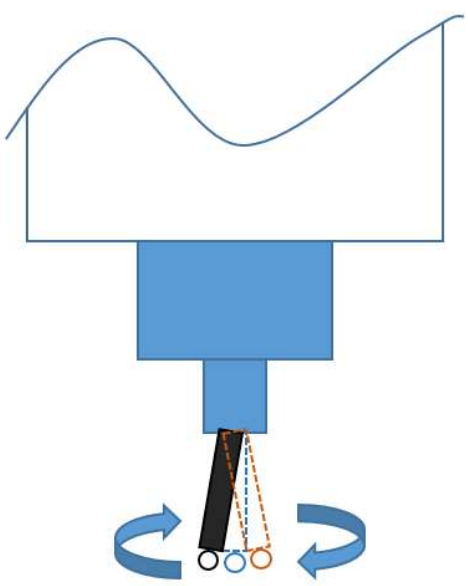

Figure 11. The Spindle Turning

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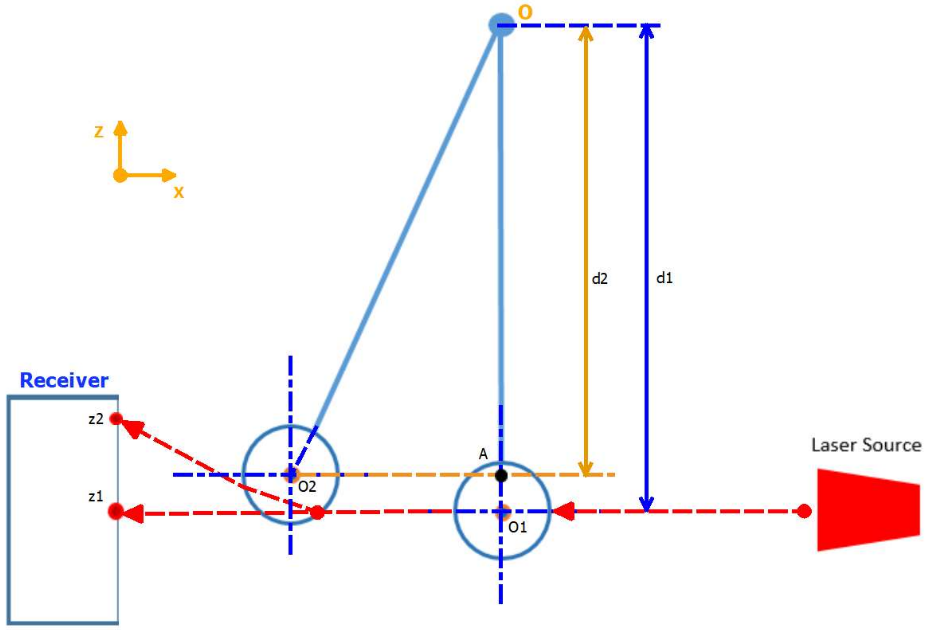

Figure 12. The

$$OO_2 = OO_1 = \sqrt{OA^2 + O_2A^2} \tag{5}$$

$$d_1 = \sqrt{d_2^2 + O_2A^2} \tag{6}$$

It is difficult to determine exactly values of O_2A, because, considering on XY coordinate, the values of O_2A is distributed following the red circle as shown in Figure 13. By using Roundness measurement, the O_2A is evaluated by Equation (7)

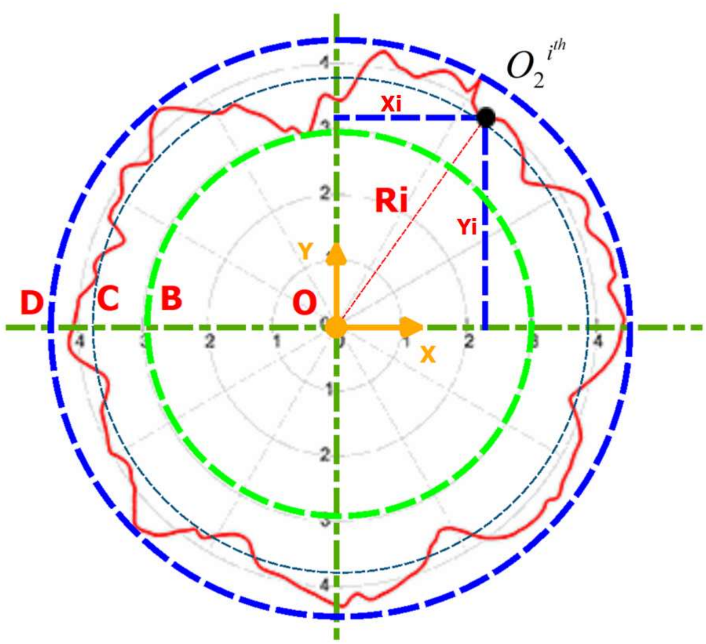

Figure 13. The Roundness Method

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$$\overline{O_2A} = \hat{R} = \frac{1}{N}\sum_{i=1}^{N} R_i \tag{7}$$

where R is an instant O_2A and N is the quantities of O_2. In this study, the N is equal to 100, then, there are 100 points distributed on the red circle Figure 13. With the R_i is calculated by Equation (8), substituting Equation (8) into Equation (7) and putting Equation (7), (9) into Equation (6), we can obtain d_1 as shown in Equation (10). Where X_i, Y_i and Z_i are achieved from Non-Bar system and d_0 is the initial length of spindle as a constant.

$$R_i = \sqrt{(X_i)^2 + (Y_i)^2} \tag{8}$$

$$d_2 = d_0 - \frac{1}{N}\sum_{i=1}^{N} Y_i \tag{9}$$

$$d_1 = \sqrt{\left(d_0 - \frac{1}{N}\sum_{i=1}^{N} Y_i\right)^2 + \left(\frac{1}{N}\sum_{i=1}^{N}\left(\sqrt{(X_i)^2 + (Y_i)^2}\right)\right)^2} \tag{10}$$

The Equation (10) written in C sharp – a programming language by using Visual Studio software is to take advantages from the computer when it receives data from non-bar system and computing based on the provided function, immediately.

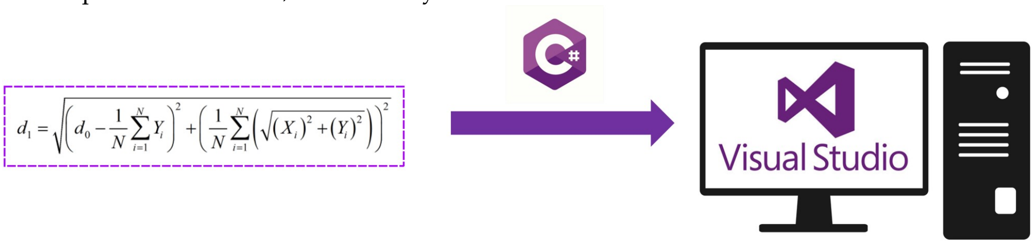

Figure 14. Programming Process

The one of many collected error data on the Z axis is shown in Figure 15, which are the differential values of d_1. We can see the first two hours, the spindle is going down 30 μm, approximately, after first two hours, something pulls it up gradually, we do not know whether it is back to zero, but at least in eight hours it is not, like shown in below. Additionally, the "30 μm" is a relative number, it seems that temperatures influence, directly proportional to it, we need an adaptive and flexible compensation function to handle various situations.

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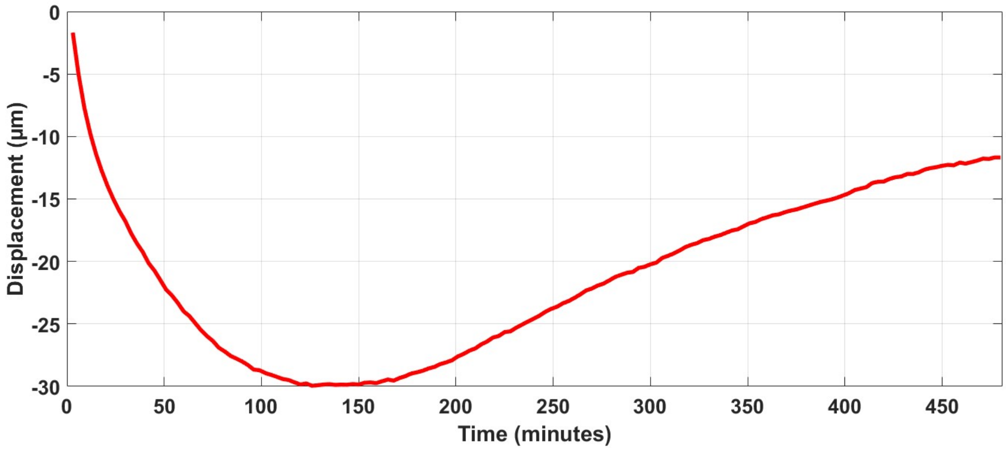

Figure 15. Errors of Spindle on Z axis

Assuming that the $B(b)$ is formed as Equation (11) with b is a variable of time. Where F is an equation from solving Equation (12). Considering the Equation (12), the $F_{(b)}$ and b are distributed in the collected error data, but multiplying with the negative sign. The $B_1 \ldots B_9$ are the coefficients, which are found by solving Equation (12).

$$B_{(b)} = \frac{dF}{db} \tag{11}$$

$$\begin{bmatrix} b_0^8 & b_0^7 & b_0^6 & b_0^5 & b_0^4 & b_0^3 & b_0^2 & b_0^1 & b_0^0 \\ b_1^8 & b_1^7 & b_1^6 & b_1^5 & b_1^4 & b_1^3 & b_1^2 & b_1^1 & b_1^0 \\ b_2^8 & b_2^7 & b_2^6 & b_2^5 & b_2^4 & b_2^3 & b_2^2 & b_2^1 & b_2^0 \\ b_3^8 & b_3^7 & b_3^6 & b_3^5 & b_3^4 & b_3^3 & b_3^2 & b_3^1 & b_3^0 \\ b_4^8 & b_4^7 & b_4^6 & b_4^5 & b_4^4 & b_4^3 & b_4^2 & b_4^1 & b_4^0 \\ b_5^8 & b_5^7 & b_5^6 & b_5^5 & b_5^4 & b_5^3 & b_5^2 & b_5^1 & b_5^0 \\ b_6^8 & b_6^7 & b_6^6 & b_6^5 & b_6^4 & b_6^3 & b_6^2 & b_6^1 & b_6^0 \\ b_7^8 & b_7^7 & b_7^6 & b_7^5 & b_7^4 & b_7^3 & b_7^2 & b_7^1 & b_7^0 \\ b_7^8 & b_7^7 & b_7^6 & b_7^5 & b_7^4 & b_7^3 & b_7^2 & b_7^1 & b_7^0 \end{bmatrix} + \begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \\ B_6 \\ B_7 \\ B_8 \\ B_9 \end{bmatrix} = \begin{bmatrix} F_{(b)} \end{bmatrix} \tag{12}$$

Now, the Equation (4) is written as Equation (13), with coefficient C_0 and coefficient C_1 coefficients:

$$F_{compen.(a,b)} = C_0 \times f(a) + C_1 \times \frac{dF}{db} \tag{13}$$

The compensation equation consists of two components, a proportional and a derivative. Those allow function more flexible and adaptive. But after several times doing experiments, $C_0 = 0.9$ and $C_1 = 0.0009$ for this study.

4. Simulations and Experiment

The equations have derived through analyzing data, which are going to be tested with simulations and experiments. The simulation is executed with Non-Bar, Temperature measurement tool and a computer integrated compensation equation. The result will reflect the efficiency of equations, if the efficiency is significant, the process will go for machining upon workpieces, if not, the data analyze will be executed again by following Figure 8.

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4.1. Simulations

To demonstrate the compensation in perspective of previous section. This will simulate compensating with the Non-bar system, with the same configurations, 9000 rpm of spindle, interval processing compensations of a minute, experiment time is eight hours as shown in Figure 16. After eight hours, the results of temperature are shown in Figure 17, the range of temperature during this process is from 20 °C to 22.5 °C, approximately.

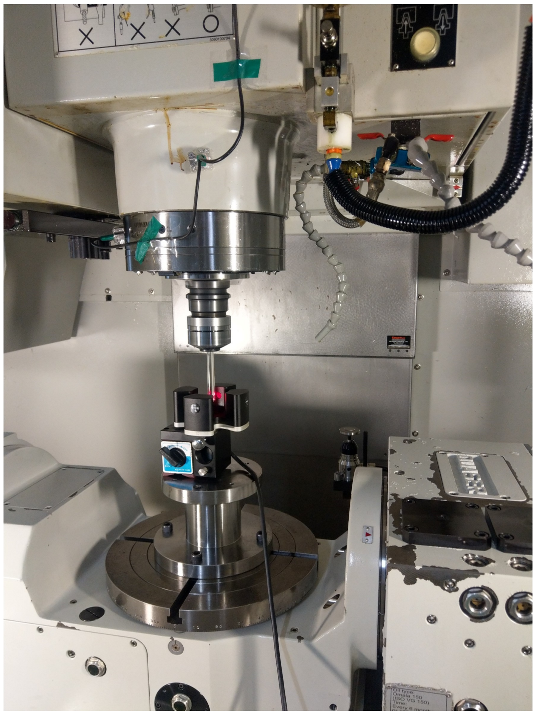

Figure 16. Simulation Process

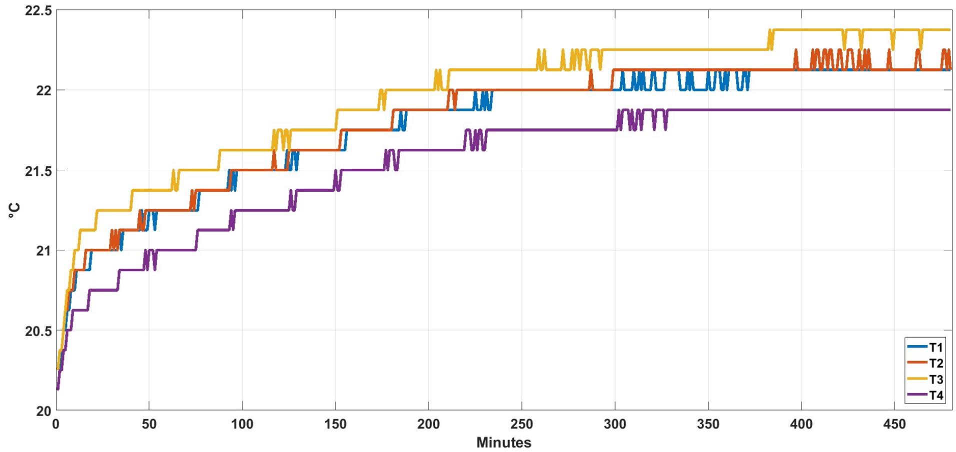

Figure 17. Temperatures

The results of error produced during experiment are shown in Figure 18. Now, we could see and make a comparison between Figure 15 and Figure 18. The errors are reduced from 30 μm to 5 μm, approximately, for this result.

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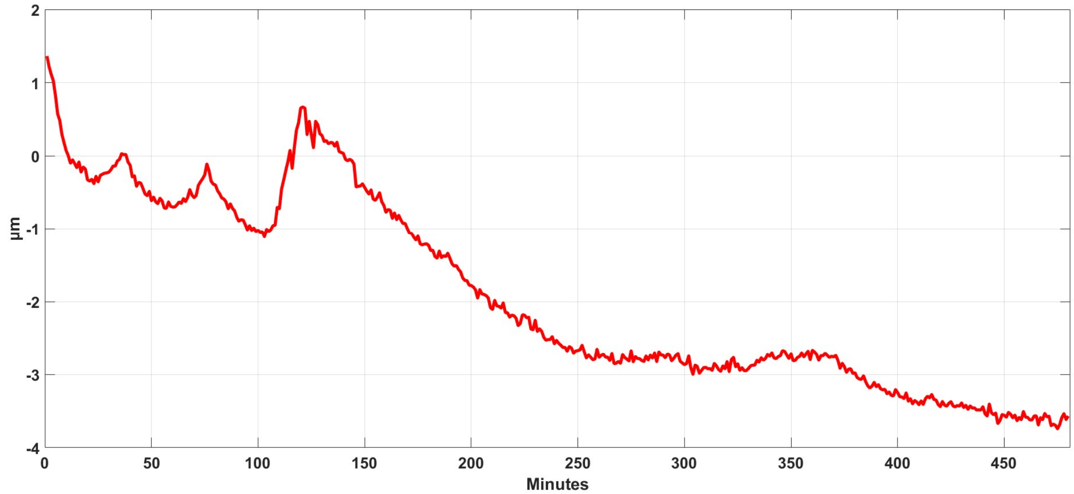

Figure 18. Results of Simulation

4.2. Experiment

Based on previous results, the experiment upon workpieces is executed with applying real-time compensation in eight hours as shown in Figure 19. The Figure 20 describes the dimensions of workpiece before and after machining on two planes, on the XY plane, the proposed cutting method is produced, the area with blue slashes is cut down 0.2 (mm) to vanish the surface roughness and the area of violet slashes is cut down 0.2 (mm) for the main purpose. On the XZ, number 1-9 are processed to verify the results of simulation and the area of number 10 is the reference area, which is used after machining time finished for measuring the errors. The dot-arrow indicate the way where cutter moving through. At the end of each line the, cutter will move up 5 (mm) to change other line. These experiment will work on two workpieces, one for compensation and one for no compensation. These two workpieces are shown in Figure 21. As mentioned at starting, we are using three-dimensional measuring instrument (ABLE-686-CNC, Jingsh Meng Technology Co. Ltd., Taichung city, Taiwan) to verify the result with 27 measured points as shown in Figure 22, then, measuring workpieces are deployed as shown in Figure 23.

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Figure 19. The Experiment

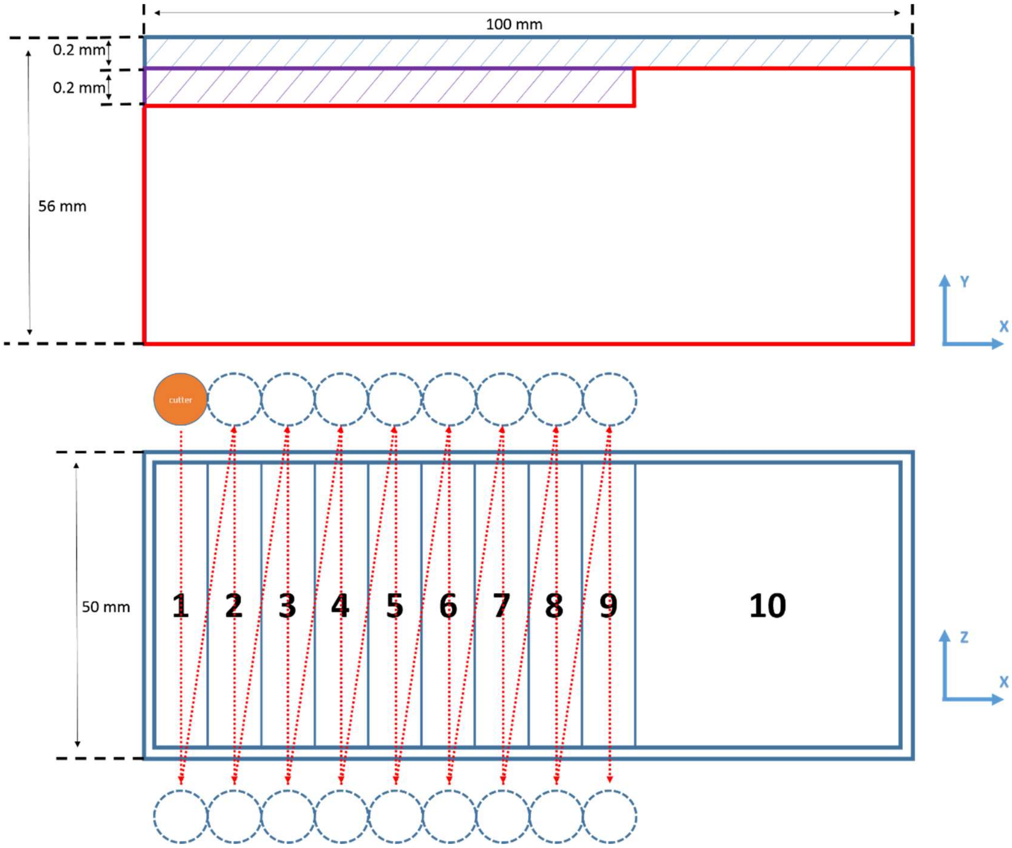

Figure 20. The Work-piece

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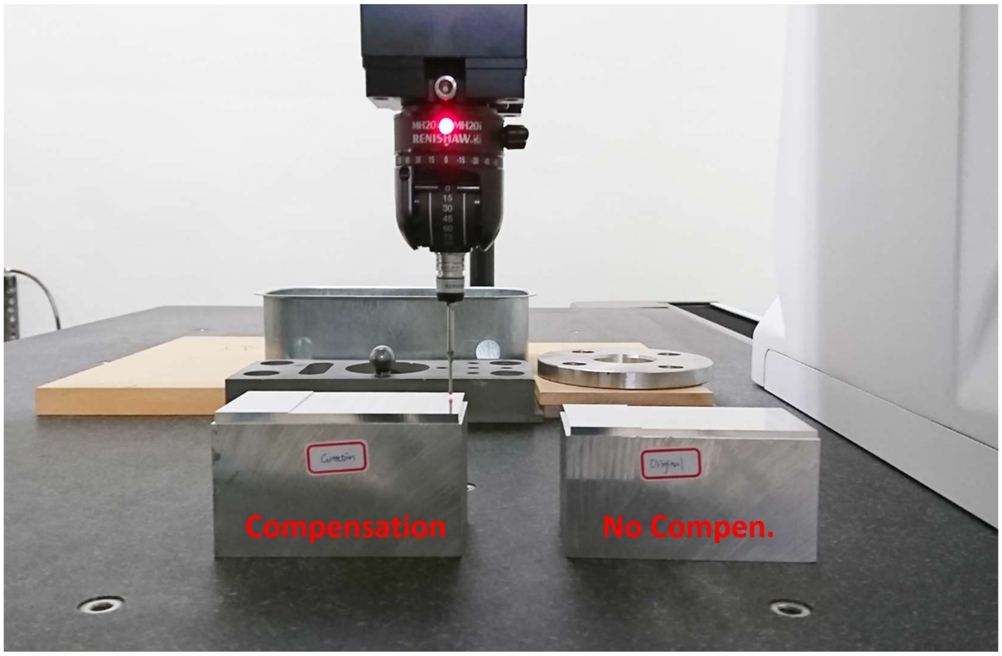

Figure 21. Results after machining

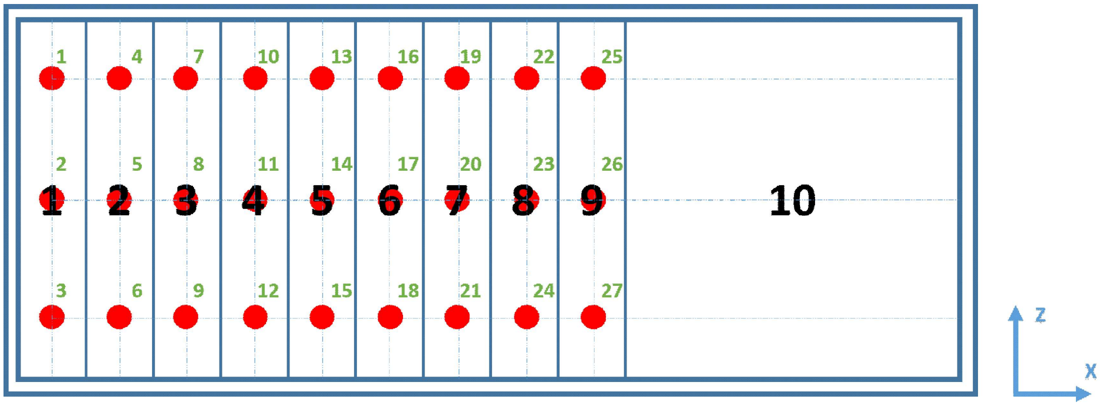

Figure 22. Measurement Method

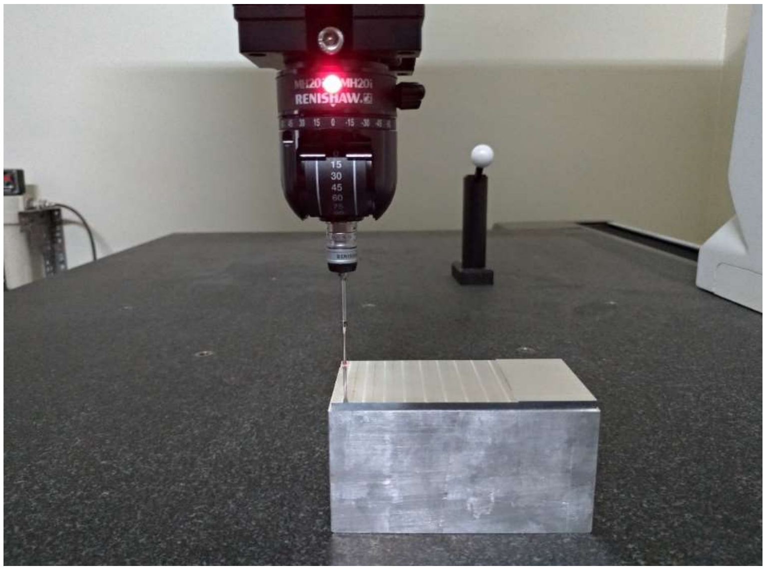

Figure 23. Measurement System

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5. Experimental Results and Conclusions

The Figure 24 shows the results from verifying by using three-dimensional measuring instrument. Observing the result, that can reflect the efficiency before and after applying real-time compensation function, the errors are improved, significantly, from 40 μm down to 10 μm, approximately. But these numbers are relative, not absolute, the values will change time to time, that is why we need a flexible function that can adapt the various scenarios. These equations provided in this study can supported many different range of temperature at starting machining time to ending machining time. We have done many simulations and the highest error is about 10 μm with utilizing real-time compensation. After the process is success, there is no need to sampling again, only need to connect the computer integrated compensation function and install temperature measurement tool to spindle for input.

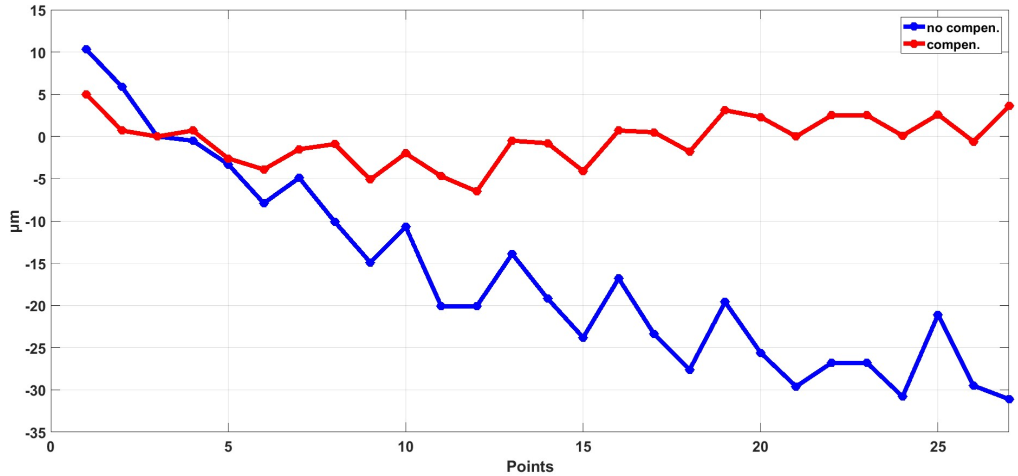

Figure 24. Experimental results

The disadvantage of this method is, the collecting data is required to generate the real-time compensation. Because, different environment or different mechanism of machine will bring back other results. Additionally, this investigation only focus on Z axis, however, there are X axis and Y axis will have effect and cause the errors. In future work, the function may provide and support real-time compensation on three axes to get better results.

Author Contributions: The authors contributed equally to the manuscript.

Funding: This research was funded by Ministry of Science and Technology (MoST) grant number MOST104-2218-E-150-001 And The APC was funded by Ministry of Education.

Acknowledgments: This research was funded by the Ministry of Science and Technology (MoST) of the Republic of China, Taiwan, and the authors gratefully express their sincere acknowledgement to MoST.

Conflicts of Interest: The authors declare no conflict of interest.

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