DEGREE PROJECT FOR MASTER OF SCIENCE WITH SPECIALIZATION IN MANUFACTURING
DEPARTMENT OF ENGINEERING SCIENCE
UNIVERSITY WEST

Effect of CNC axis movement on the surface roughness in milling

Yuan Liu

UNIVERSITY WEST

Summary

In this paper, the performance of a new measurement system CITE (CNC Integrity Tracing Equipment) is investigated. CITE measurement system is the name given to the data acquisition hardware and software developed by University West for recording the movements of CNC machine tools. It can be used for monitoring of the milling process and recording the milling errors. The aim of this study is investigate the capability of the CITE system in prediction of the surface roughness. In an example cutting test, the CITE measurement system was used for recording selected sections in straight milling process and curved milling process. After that, surface roughness, predicted by the CITE measurement system, was compared with the CMM (Coordinate measurement machine). The investigation shows that the CITE measurement system is comparable to the CMM for evaluation of roughness in curved sections. In straight sections, the evaluation of roughness by CMM machine is close to the simulation values that predicts surface roughness considering tool run-out.

Date:	June 8, 2015
Author:	Yuan Liu
Examiner:	Jari Repo
Advisor:	Mahdi Eynian, University West
Programme:	Master Programme in manufacturing
Main field of study:	Manufacturing
Credits:	60 Higher Education credits (see the course syllabus)
Keywords	Milling process, axis movement, surface roughness, tool run-out
Publisher:	University West, Department of Engineering Science, S-461 86 Trollhättan, SWEDEN Phone: + 46 520 22 30 00 Fax: + 46 520 22 32 99 Web: www.hv.se

Preface

This thesis project was completed at the University West and Production Technology Centre in Trollhättan, Sweden. The CITE measurement system is developed at University West and funded by the Vinnova COMPIT project.

I would like to thank Dr. Mahdi Eynian, University of West, for the guiding of this research and providing the raw data from the CITE and CMM measurement system. It is my honour to be your student.
I would also like to thank Dr. Jari Repo who helped me revise the thesis and have a deeper understanding of the CITE measurement system.

It is my honour to study in University West. Thank you all for helping me in my masters study.

Affirmation

This master degree report, *Effect of CNC axis movement on the surface roughness in milling,* was written as part of the master degree work needed to obtain a Master of Science with specialization in manufacturing degree at University West. All material in this report, that is not my own, is clearly identified and used in an appropriate and correct way. The main part of the work included in this degree project has not previously been published or used for obtaining another degree.

Yuan Liu

Signature by the author

2015-06-08

Date

Yuan Liu

Contents

Preface

Main Chapters

Symbols and glossary

CITE	CNC Integrity Tracing Equipment
CMM	Coordinate Measurement Machine
R_z	Maximum roughness depth
f_t	Feed per tooth
N_z	Number of cutting edges on the tool
R	Tool Radius

1 Introduction

Compared with conventional milling machines, the CNC milling machines are widely used in aerospace and automobile industries due to high production rate, wide processing range, good surface quality and flexibility. One of the major advantages of the CNC milling process is the possibility to machine complex surfaces. Hence many studies in recent years have focused on increasing the surface quality. The surface quality affect the performance of the processed parts in a wide range of applications.

On the basis of the concept of surface finish [1], the surface finish is a critical issue which reflects the surface integrity and performance caused by tools. Surface finish is considered as one of the most common ways to define surface quality. In current mechanical manufacturing area, there are some popular methods [2] that have influenced on the surface finish (see Figure 1).

The surface roughness is the most important component of the surface finish that can be used as evaluation criteria. But, it's very difficult to predict the surface roughness by using mathematical equations. So, many researchers have focused on building models with different parameters to predict the surface finish.

In general, in terms of quality control, cutting speed and feed rate were most commonly used in the models. Folea [3] utilized the roughness prediction model by controlling cutting speed in high speed milling and Çolak [4] introduced GEP (gene expression programming) algorithm into the model for aluminium, after tests, they stated that the lower roughness can be obtained by higher cutting speed. On the other hand, Ding [5] made use of the surface generation algorithm model in 2D vibration-assisted micro-end-milling, the result was that the surface roughness will decrease with increasing of feed rate, and Kasim [6] got the same result by using response surface methodology and BOX-Behnken design.

Except theses parameters, the effect of tool characteristics has become a new research area on surface roughness prediction. Buj-Corral [7] developed a model for predicting the roughness profile based on number of teeth and tool diameter, after simulation of the roughness profile, he found at low feed values, low roughness was obtained by low number of teeth and high tool diameter. Yang [8] proposed a model to predict the surface roughness

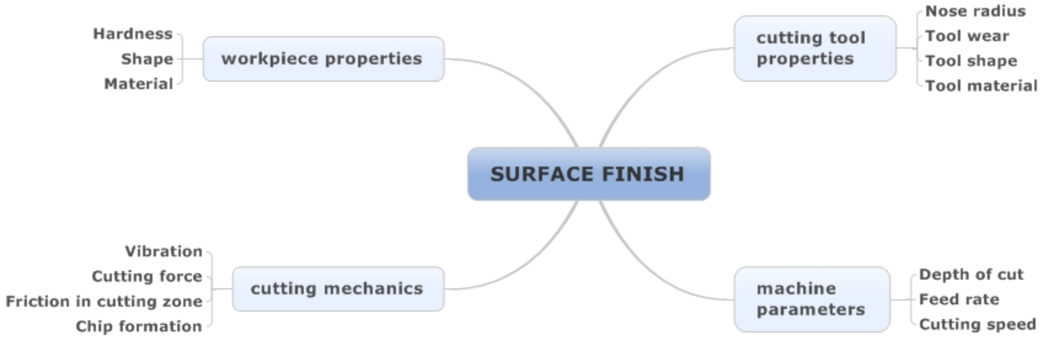

Figure 1 Influencing factors on surface finish

based on the sources of machining errors, such as run-out, tilting, tool deflection and workpiece displacement. According to this model, the deflection of the tool which includes static and dynamic parts is the foremost factor on the surface roughness. Because there are variations in the tooth-insert radial locations, run-out, that will causes the change of chip load on the individual teeth, and this change will affect the surface roughness [9]. Therefore, investigating the effects of run-out of the tool has become a further research direction for roughness prediction. As expected, the roughness will increase with the feed per tooth for some of the teeth, but Schmit [10] investigated that under constant feed per tooth, the roughness will increase and then decrease when run-out is becoming bigger. In addition, Wojciechowski [11] put forward the run-out and dynamical phenomenon will result in tool displacement, and the displacement plays a major role in surface roughness height. In the model that focused on the geometry and kinematics of the cutter [12], it showed that the deflection of the tool and workpiece will result in machining errors since the tool run-out will influence on the machining errors distribution along the axis direction. Costes [13] summarized the previous research and presented a method, which suggests that the deflection caused by run-out influences the surface roughness by creating the height variations of the tool end.

In a previous work Repo has investigated the possibility of detecting tool wear from studying the position signals in a machine tool [14]; However, it is found that in the previous literature few people have considered or investigated the imperfections of the drive mechanism of the machine's table on the roughness of the manufactured part.

This study uses the CITE measurement system to collect the axis movement, then extract surface roughness values assessed by errors in movement. The values are compared with data acquired from the CMM (Coordinate Measurement Machine). The aim of this paper is researching the accuracy of surface roughness prediction from internal signals and comparing with encoder recordings from a milling process and investigate the effect of unwanted movements and positioning errors on the surface roughness.

In this paper, in addition, the geometric errors were considered for a tool that had run-out. Modeling of run-out can explain the amount of roughness in some sections of the experiments.

2 Method

2.1 Experiment

The samples were machined in a 3 axis milling machine. The method of machining process used in this study was end milling. The machining parameters are presented in Table 1.

Table 1. Machining parameters

Tool diameter	Tool flute	Spindle speed	Cutting speed	Feed per tooth	Depth of cut	Width of cut
10 mm	3	2546 rev/min	80 m/min	0.08 mm/tooth	3 mm and 4 mm	10 mm

The size of the samples is 270×100×25mm, the material of the samples is low carbon steel (S355J2 Steel), the composition can be seen in Table 2.

Table 2. The composition of S355J2 steel (Standard: EN 10025-2:2004)

C %	Si %	Mn %	P %	S %	Cu %	CEV %
max 0.22	max 0.55	max 1.6	max 0.03	max 0.03	max 0.55	max 0.47

The geometry of the machined part is shown in Figure 2. Because of its shape, the test is called S-Test, as shown in Figure 3. In the actual machining process, the blue fine line is the actual milling cutter movement. The blue arrow represents the tool feed direction and the red arrow indicates the direction in tool idle movement.

In step one, the tool starts from the original point (X = -36, Y = -12, Z = 20), after fed to the machined surface, the tool produces the S curve finished face by following the blue line path and stops at point (X = 36, Y = 12, Z = 0).

In step two, the tool rises and moves to the point (X= 0, Y= -42, Z = 0) along the red arrow direction.

In step three, the tool follows the blue arrow direction and stops at point (X=-75, Y=-42, Z=0).

In step four, the tool rises and travels to the point (X=0, Y = -42, Z=20), then it lowers and machines the stretch along the direction from X=0 to X=-75.

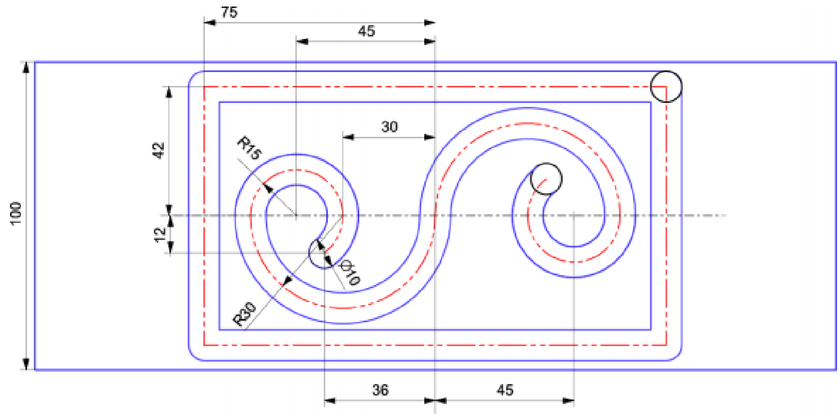

Figure 2 Dimensions of the machined sample (source: [15], used with permission)

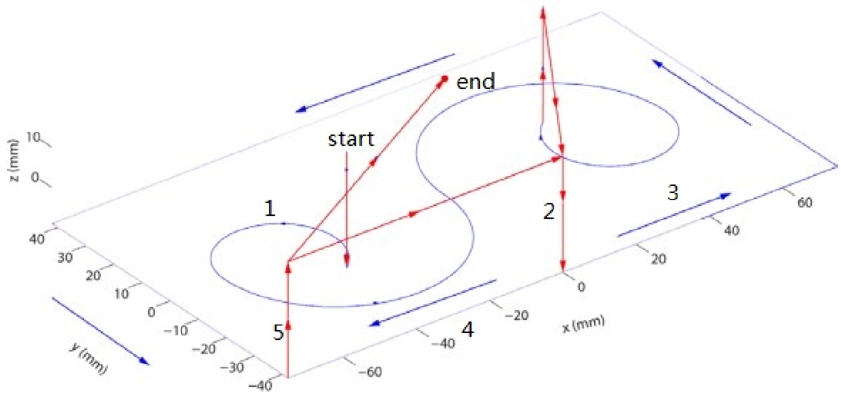

Figure 3 Path for the S-test (source: [15], used with permission)

In step five, the tool stops and moves to the final point (X=0, Y=0, Z=20).

During the milling process, the tool data, like coordinate points and errors on the XY plane, were obtained by the linear encoders in the milling machine and recorded by the CITE measurement system. After the milling process, the samples were measured by the CMM. In order to analyse the surface finish numerically, MATLAB was used for converting the discrete data into a surface profile and simulating the milling process, then calculating surface roughness depth R_z in different positions.

2.2 Simulation of the effect of run-out on roughness

The simulation process is achieved by the software MATLAB on account of its powerful mathematical function and excellent visualization function.

2.2.1 Surface roughness measurement

There are two methods to measure surface roughness in this paper: one way is the conventional CMM measurement, the other way is the innovative Internal Sensors measurement from the CITE system. Using these two methods, the data can easily be recorded in the computer.

Compared with conventional profileo-meter, CMM machine is more time-saving. On the other hand, a measurement by CMM provides information about both the shape errors in addition to the roughness of the machined surface. In the CMM measurements, the samples were measured with continuous probing. The diameter of the probe was 1.5 mm and the results of the probing were saved in a text file. These files could be uploaded and studied in the CITE measurement system. The main advantage of the CITE system is the possibility for the simultaneous comparison of internal sensor's data and CMM machine's data. With this function, it is easy to compare the difference between the two methods.

In previous research, the machined samples were usually measured by CMM or profilemeters after milling process. These methods cannot monitor the milling process in real time to adjust the milling parameters for better surface quality and find the sources for surface finish problems. Therefore, introducing an internal sensors measurement system into the CNC machine is a development in a new direction.

The CITE measurement system is a user-friendly hardware and software system for CNC machine tools. It records the encoder signals to monitor the CNC machine tool's movements that influence the sample's surface quality. In this system, a data acquisition hardware with optional force dynamometer is connected to the CNC machine, meanwhile this hardware sends the signals to the computer with CITE measurement system via a USB cable. The

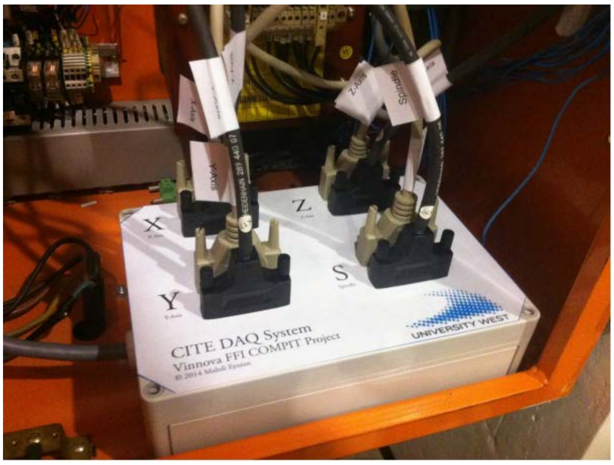

Figure 4 The CITE hardware for data acquisition, inside CNC machine's control cabinet (source: [15], used with permission)

CITE measurement system is used for collecting, saving and processing the data. Figure 4 shows the hardware of the CITE system in the CNC's control cabinet connected to the encoder lines for the spindle and different feed axes of the machine tool.

2.2.2 Simulation of surface roughness

During the milling process, the movement of the tool with respect to the workpiece was recorded by the CITE measurement system. In order to investigate the surface finish, from internal sensors, eight equal length sections (named 1-8) were selected in the rectangle path and four sections (A-D) in the curve path for calculating the surface roughness (See Figure 5a). For CMM measurement, the calculation sections were arranged in the same position as the 8 sections in rectangle path in internal sensors measurement. Figure 5b shows the sketch for the CMM measurement path.

After selecting the calculation sections, the data was transformed to surface profile. In this investigation, the least-squares method was used for removing the linear trends in the data.

Usually, the surface profile consists of waviness, roughness and form deviation. The presence of the waviness and form deviation will affect the calculation of the roughness. So, before analysing the surface roughness, it should be filtered to separate waviness and form deviation from the surface data.

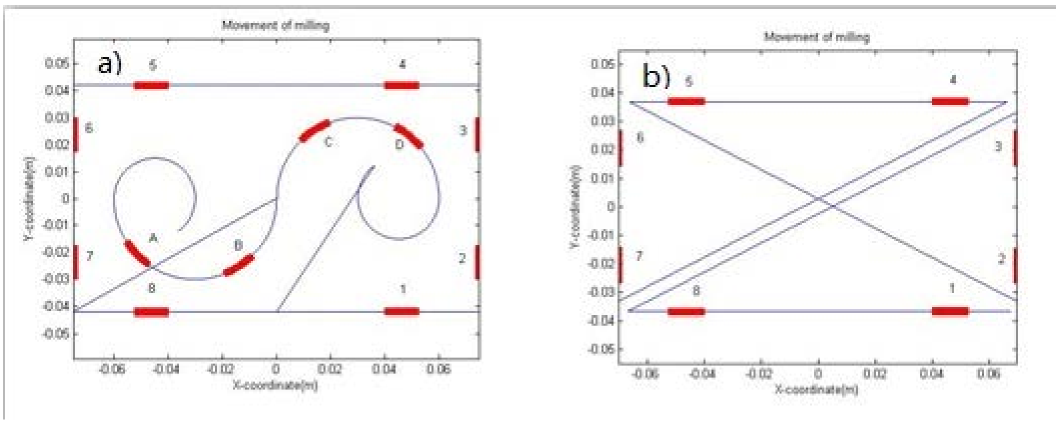

Figure 5 a) Calculation sections for internal sensors measurement samples **b)** Calculation sections for CMM measurement samples

In recent industrial application, the Gaussian filter is widely used for separating the shape errors from the roughness for calculating the surface roughness. This filter is low-pass filter. One of the advantages of the Gaussian filter is zero-phase property [16], when it is applied in forward and reverse directions, it does not shift the phase between the wavelengths. It always suppress the wavelengths under and near the cut-off length.

By observing the surface profile, the mean width of profile elements R_{sm} was measured as 1.2 mm. According to the standard of DIN EN ISO 4288 and ASME B46.1, R_{sm} in this paper is in the prediction range for profiles from 0.4 mm to 1.3 mm, so the cut-off length λ_c is equal to 2.5mm. The standard evaluation length is five times as cut-off so each section in measurement samples was set at 12.5 mm.

2.2.3 Geometrical calculation of roughness considering run-out

Based on the theory of machining, the surface roughness can be analysed by milling parameters. As published by Stephenson [2] in the ideal milling process, using a tool without radial run-out, the theoretical maximum roughness depth R_z can be calculated by the feed per tooth and tool radius:

$$R_z = \frac{f_t^2}{8R} \tag{1}$$

where f_t is the feed per tooth and R is the tool radius.

In the actual milling process, the surface can be defined as the envelop surface produced by the cutter edge along the feed direction. The envelope surface was controlled by the vibration between the tool and workpiece, the tool geometrical parameters and the tool run-out. In order to calculate the roughness with cutter run-out, this paper method introduced by Franco [17] and Denkena [18] that based on the tool end trace.

3 Results

After the measurement, the result from the CMM machine, the CITE measurement system and simulation is obtained and compared.

3.1 Calculating the roughness for the sections in rectangle path

Since the measurement in the rectangle path is a linear path, the shape error is small and thus ignored in this paper. Under this condition, the least square is used for removing the linear trend. Based on a large number of discrete data, the roughness profile can be produced.

In all experiments, each set of the measurement was obtained under the condition of spindle speed of 2546 rev/min. For both Internal Sensors measurement and CMM machine measurement in rectangle path, the only difference is depths of cut: one is 3 mm and the other is 4 mm. The results of the calculated roughness are shown below (Table 3a and Figure 3b).

Table 3a The $\boldsymbol{R_z}$ for depth of cut =4 mm (**μm**)

Section	1	2	3	4	5	6	7	8
Internal sensors	0.0368	0.0839	0.0620	0.0480	0.0369	0.0532	0.0480	0.0344
CMM	3.99	4.49	4.60	3.88	3.81	4.34	5.45	3.97

Table 3b The $\boldsymbol{R_z}$ for depth of cut =4 mm (**μm**)

Section	1	2	3	4	5	6	7	8
Internal sensors	0.0456	0.0680	0.0685	0.0780	0.0778	0.0608	0.0690	0.0627
CMM	4.54	3.15	3.00	3.91	4.45	3.62	3.95	3.85

According to the values in the two tables, this study compared the two different roughness measurements, the Internal Sensors measurement (see Figure 6) and CMM machine measurement (see Figure 7).

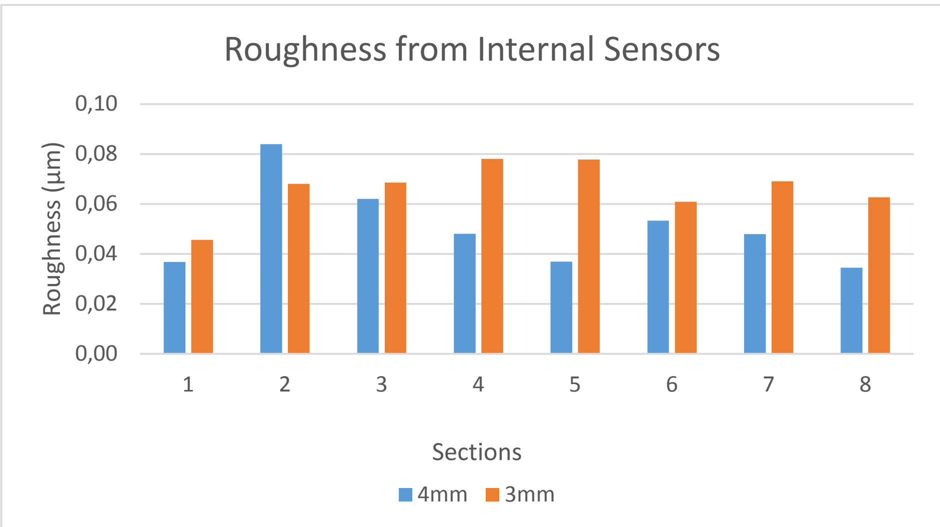

Figure 6 The $\boldsymbol{R_z}$ from the internal sensors measurement

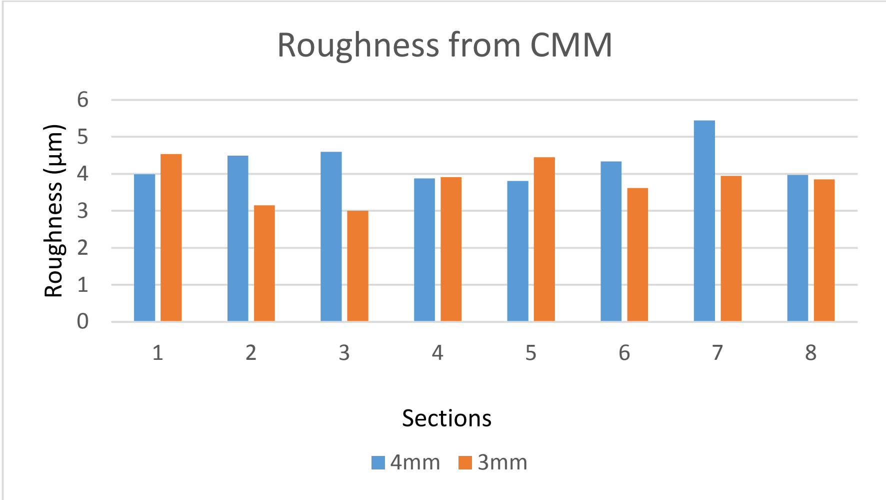

Figure 7 The $\boldsymbol{R_z}$ from the CMM machine measurement

In these figures, for the CMM machine measurement, in section 1 and 5, the roughness in 3 mm cut is larger than 4 mm cut. This can be explained that measurement for CMM machine was very close to the precision of the method and not using a small enough sampling length.

By help with the CITE measurement system monitoring function, the errors were recorded. Samples in the rectangle sections were chosen to calculate the max peak-to-valley height, as can be seen in Figure 8a and 8b. In the Figure 8a, the max peak-to-valley height was about 0.03 µm. In the Figure 8b, the value was 3 µm.

3.2 Calculating the roughness for the sections along curved path

The curve data was recorded by the CITE measurement system using a spacing of 2.5 μm. The length of each section was 12.5 mm as illustrated in Figure 5a. The CMM machine measurement was recorded as the inner path and outer path.

In the curved path, along with the change of feed force in the process of milling, the shape error will exist in the surface profile. Therefore, this study used Gaussian filter with

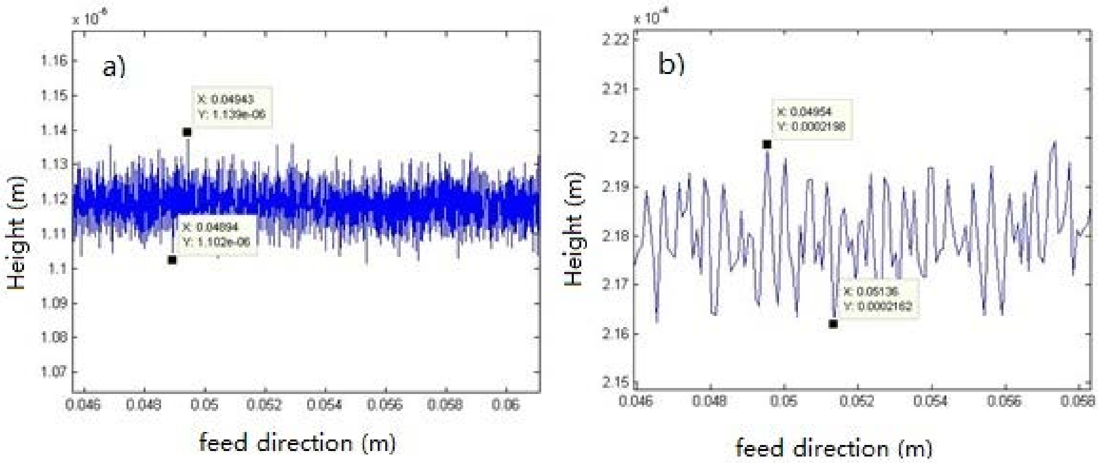

Figure 8 a) The small samples in internal sensors measurement errors **b)** The small samples in CMM machine measurement errors

2.5 mm cut-off length to separate the waviness and roughness from the original surface profile.

After filtering of the roughness profile, the roughness can be calculated. The results of the 4 curve sections are shown in Table 4a and 4b. The values are labelled in the bar diagram (Figure 9 and Figure 10). As shown in the diagram, the R_z values of each section for different depths of cut are quite similar.

Table 4a The $\boldsymbol{R_z}$ (**µm**) for depth of cut =4 mm

Section	A	B	C	D
CMM machine inner path	7.75	8.63	5.73	6.25
CMM machine outer path	6.99	7.02	6.87	6.79
Internal sensors	8.05	7.94	8.21	8.87

Table 4b The $\boldsymbol{R_z}$ (**µm**) for depth of cut =3 mm

Section	A	B	C	D
CMM machine inner path	9.12	8.6	6.2	6.76
CMM machine outer path	6.32	7.18	6.6	8.08
Internal sensors	7.28	4.72	8.27	9.42

In these figures, it can be found that in sections A and B, the roughness of inner path is larger than outer path. However in sections C and D, the roughness of inner path is smaller.

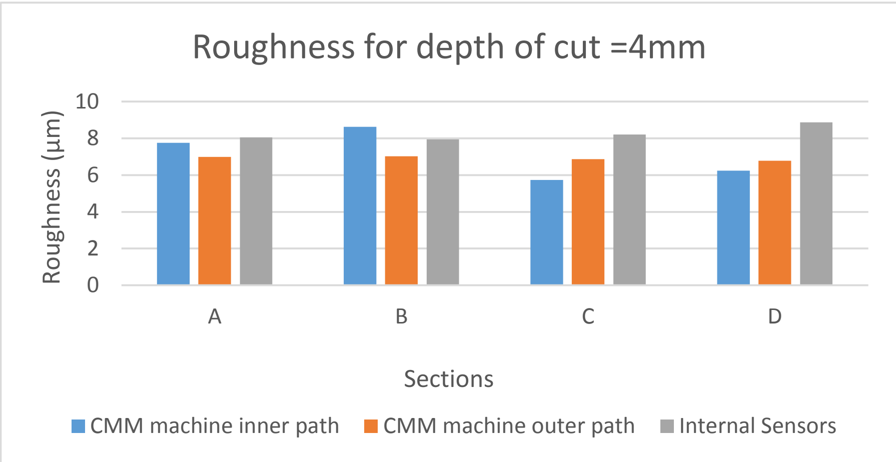

Figure 9 The $\boldsymbol{R_z}$ for depth of cut equal to 4 mm

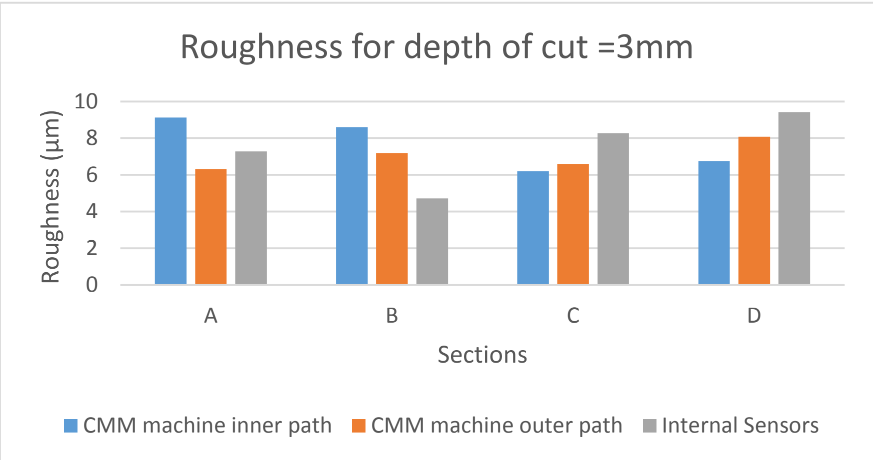

Figure 10 The $\boldsymbol{R_z}$ for depth of cut equal to 3 mm

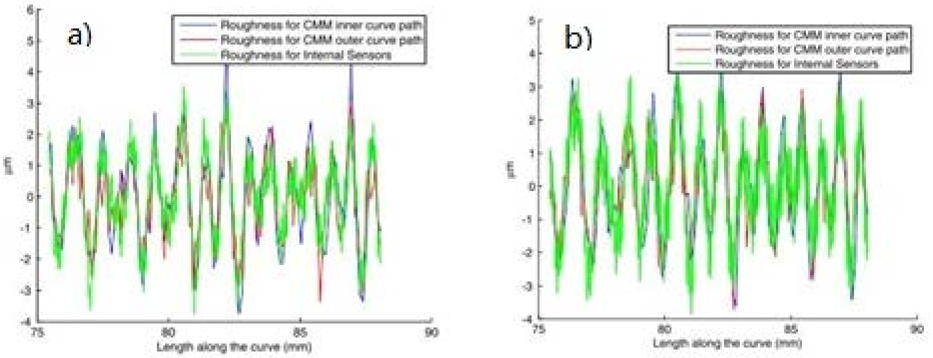

Figure 11 a) The roughness for depth of cut equal to 3 mm **b)** The roughness for depth of cut equal to 4 mm

This can be explained by the inner path in A and B and the outer path in C and D is generated by up-milling where same rubbing occurs before start of cutting.

The filtered roughness profiles are shown in Figure 11a and 11b.

Compared with two figures, it can be observed that the internal sensors measurement values have a good agreement with CMM machine measurement values. In addition, the roughness was not sensitive to the depth of cut.

3.3 Calculation of the R_z with run-out

Without the radial run-out in the tool, the R_z in this case can be calculated by feed per tooth f_t and nominal tool radius R [2]. In this case, the trace was made by all the three teeth since the circles of the tool that produce the trace in every feed per tooth. But if there existed the radial run-out, the trace will be only made by one tooth (see Figure 12). So, the circles which made the trace will be placed every N_z times feed per tooth. The following formula describe the calculation of the R_z:

$$R_z = \frac{(N_z \times f_t)^2}{8R} = 1.44\ \mu\text{m} \qquad (2)$$

where N_z is the tool flutes.

In order to calculate the R_z in this condition, MATLAB was used for simulating the tool path along the feed direction. The tool end path can be considered as envelop curve that generated by the circles. The envelope curve along bold line is the surface profile that corresponds to the trajectory of the cutting edge teeth (see Figure 12).

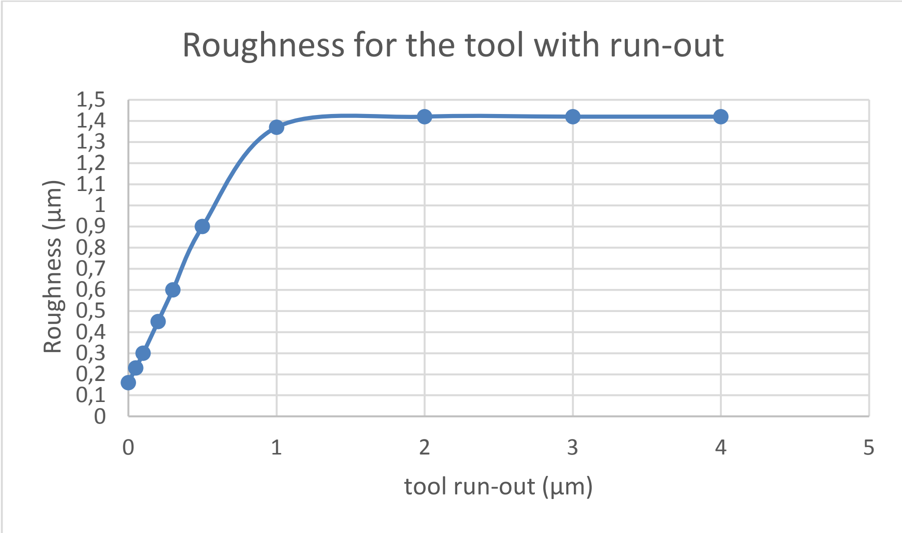

Figure 13 Roughness for the tool with run-out

In this study, it chose 10 different radial run-out values. The result is shown below:

Table 5 Simulated roughness for different run-outs

Run-out (**µm**)	0	0.05	0.1	0.2	0.3	0.5	1	2	3	4
Roughness (**µm**)	0.16	0.23	0.3	0.45	0.6	0.9	1.37	1.42	1.42	1.42

The diagram for these results can be seen in Figure 13. According to the diagram, for constant feed per tooth, the roughness values are increasing with radial run-out. The values of roughness are close to the one measured in the straight cutting sections (1-8). When the run-out value exceeds 1µm, the roughness curve stabilizes around 1.44 µm.

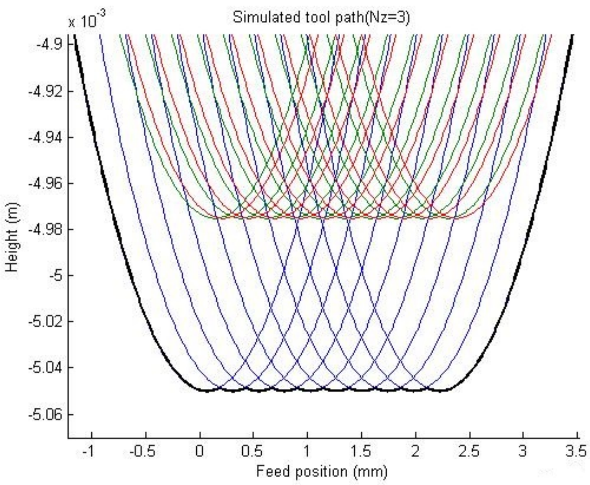

Figure 12 Simulated tool path

4 Discussion and conclusions

This paper studied a new measurement system for online estimation of the surface roughness on the milled parts. This method works by collecting information from the positioning system of a machine tool. Unlike measuring by CMM or conventional profilometer, it does not add an additional process to the manufacturing chain therefore it could be an interesting system if it could predict the surface qualities of the machined parts with acceptable precision.

In this investigation, the results of this system are compared with the results of the roughness measurement by a CMM machine. The results of the investigation and simulation show that:

1. In curved sections, the errors along the radial direction measured by CITE measurement system were reflected on the part's geometry and surface finish, the values were similar to the values measured by the CMM machine. In many instances, the roughness curves calculated from the internal sensors matched those measured by the CMM machine. Comparing Figure 9 and Figure 10, the roughness for the 3 mm cut is similar to the roughness for the 4 mm cut. This suggests that the roughness and machine axis errors in this section are independent of the cutting loads.

2. In straight sections, the roughness values measured by the CITE measurement system were about 100 times smaller than the values measured by the CMM. In generation of these straight sections, one axis of the machine tool was supposed to remain stationary; but the CITE measurement system was able to measure movements on the order of 0.03 μm; however, based on the CMM measurement, the values of roughness in these sections were as large as 2 μm. This value is close to the value predicted for the roughness created by a tool that has a run-out larger than 1 μm.

In summary, in the investigated machine tool and operation, the errors in the movements of the machine's axis are large, about 8 μm, even excluding the direction reversal errors which were reflected on the parts surface and were possible to measure using the CITE measurement system.

There are still some limitations in this research. In this paper, the parts have been machined by the same 3-axis milling machine. A comparison between multiple machine tools could have given insight in the sources of the surface roughness in a wider range of machine tools. Moreover, only two different depths of cuts, with a single spindle speed and feed rate were used in these trails. It is not known how the machine would behave in a considerably faster or slower cutting or considerably bigger or smaller feed per tooth.

In a future work, different milling machines and more milling parameters could be studied. Also, the effect of depth of cut on the roughness values for CITE measurement system could be further investigated.

5 References

[1] G. P. Petropoulos, C. N. Pandazaras, and J. P. Davim, "Surface texture characterization and evaluation related to machining," in *Surface integrity in machining*, ed: Springer, 2010, pp. 37-66.

[2] D. A. Stephenson and J. S. Agapiou, *Metal cutting theory and practice* vol. 68: CRC press, 2005.

[3] M. Folea, D. Schlegel, N. Lupulescu, and L. Parv, "Modeling surface roughness in high speed milling: cobalt based superalloy case study," in *Proceedings of 1st International Conference on Manufacturing Engineering Quality Production System*, 2009, pp. 353-357.

[4] O. Çolak, C. Kurbanoğlu, and M. C. Kayacan, "Milling surface roughness prediction using evolutionary programming methods," *Materials & design,* vol. 28, pp. 657-666, 2007.

[5] H. Ding, S.-J. Chen, and K. Cheng, "Dynamic surface generation modeling of two-dimensional vibration-assisted micro-end-milling," *The International Journal of Advanced Manufacturing Technology,* vol. 53, pp. 1075-1079, 2011.

[6] M. S. Kasim and M. A. Sulaiman, "Prediction surface roughness in high-speed milling of Inconel 718 under MQL using RSM method," *Middle-East Journal of Science Research,* vol. 13, pp. 264-272, 2013.

[7] I. Buj-Corral, J. Vivancos-Calvet, and H. González-Rojas, "Roughness variation caused by grinding errors of cutting edges in side milling," *Machining Science and Technology,* vol. 17, pp. 575-592, 2013.

[8] D. Yang and Z. Liu, "Surface plastic deformation and surface topography prediction in peripheral milling with variable pitch end mill," *International Journal of Machine Tools and Manufacture,* 2014.

[9] H. Li and X. Li, "A numerical study of the effects of cutter runout on milling process geometry based on true tooth trajectory," *The International Journal of Advanced Manufacturing Technology,* vol. 25, pp. 435-443, 2005.

[10] T. L. Schmitz, J. Couey, E. Marsh, N. Mauntler, and D. Hughes, "Runout effects in milling: surface finish, surface location error, and stability," *International Journal of Machine Tools and Manufacture,* vol. 47, pp. 841-851, 2007.

[11] S. Wojciechowski, P. Twardowski, and M. Pelic, "Surface texture generation during cylindrical milling in the aspect of cutting force variations," in *Journal of Physics: Conference Series*, 2014, p. 012017.

[12] X. Liu and K. Cheng, "Modelling the machining dynamics of peripheral milling," *International Journal of Machine Tools and Manufacture,* vol. 45, pp. 1301-1320, 2005.

[13] J. P. Costes and V. Moreau, "Surface roughness prediction in milling based on tool displacements," *Journal of Manufacturing Processes,* vol. 13, pp. 133-140, 2011.

[14] J. Repo, "Condition Monitoring in Machining Using Internal Sensor Signals" TRITA IIP 12-06, Doctoral thesis, KTH: Stockholm.

[15] M. Eynian, "User Manual for CITE Measurement System," Trollhättan2015.

[16] B. Muralikrishnan and J. Raja, *Computational surface and roundness metrology*: Springer Science & Business Media, 2008.

[17] P. Franco, M. Estrems, and F. Faura, "Influence of radial and axial runouts on surface roughness in face milling with round insert cutting tools," *International Journal of Machine Tools and Manufacture,* vol. 44, pp. 1555-1565, 2004.

[18] B. Denkena, M. Krüger, D. Bachrathy, and G. Stepan, "Model based reconstruction

of milled surface topography from measured cutting forces," *International Journal of Machine Tools and Manufacture,* vol. 54, pp. 25-33, 2012.