ISSN 1330-3651
UDC/UDK 621.923.6.014.08:681.518.3

A MEASUREMENT SYSTEM FOR THE FABRICATION INSPECTION OF LINEAR AND ROTARY AXES IN A 5-AXIS TOOL GRINDER

Yung-Cheng Wang, Chi-Hsiang Chen, Bean-Yin Lee, Tun-Hao Liang,Te-Shing Chung

Original scientific paper
Due to rapid developments in the modern cutting technology, the demand for all kinds of high precision tools has been relatively increased. The final processing of tools denotes the grinding of the cutting edge which is known as the most important procedure. It is also a critical issue for determining the geometrical profiles, cutting performance, and tool life. Therefore, this study is concerned with the development of a measurement system for the error analysis and compensation of linear and rotary axes during the fabrication process of a 5-axis tool grinder. The results show that the dimensional accuracy of the diameter will be enhanced to 0,002 mm with the positioning compensation. And the spiral geometrical accuracy will be improved to 0,011 degrees. Hence it can be proved that the performance of a tool grinder has been promoted and its precision and quality have also been significantly improved with the aid of the proposed measurement system for a 5-axis tool grinder.

Keywords: *error compensation, linear and rotary axes, 5-axis tool grinder*

Mjerni sustav za nadzor izrade linearnih i rotacionih osovina u 5-osovinskoj alatnoj brusilici

Izvorni znanstveni članak
Zahvaljujući brzom razvoju moderne tehnologije rezanja, relativno je porasla potražnja za svim vrstama alata za preciznu obradu. Završna obrada alata odnosi se na brušenje rezne oštrice što je poznato kao najvažniji postupak. Također je bitna kod određivanja geometrijskih profila, učinka rezanja, i radnog vijeka alata. Stoga se ovaj rad bavi razvojem mjernog sustava za analizu grešaka i kompenzaciju linearnih i rotacionih osovina tijekom izrade 5-osovinske alatne brusilice. Rezultati pokazuju da će se dimenzijska točnost promjera povećati na 0,002 mm popravljanjem pozicioniranja. Također će se i spiralna geometrijska točnost poboljšati na 0,011 stupnjeva. Stoga se može utvrditi da je učinkovitost alatne brusilice povećana i da su joj preciznost i kvaliteta također značajno poboljšani pomoću predloženog mjernog sustava za 5-osovinsku alatnu brusilicu.

Ključne riječi: *kompenzacija greške, linearne i rotacione osovine, 5-osovinska alatna brusilica*

1 Introduction

CNC tool grinder is the product of mechanical and electrical technology integration. It needs higher precision and reliability in comparison with general machine tools. The processing accuracy is very important for determining the quality of a machine. There are lots of parameters affecting the processing accuracy, e.g. performance control, assembly quality and geometrical errors etc.

There are various factors affecting the machine tool precision, overall the error can be divided into kinematic error and static error, while the static error contains the geometrical errors. The static errors contribute 70 percents of precision error in the machine tool production process [1]. The effects of geometric error and thermal deformation on the accuracy of three-axis machine tools have been widely studied [2, 3]. In the study [4] about the R-test detection of five-axis machine tools, three sensor probes with a standard 2-axis measurement sphere moving in 2D space have been analyzed. Measurements along the *Y*-axis and the *Z*-axis show an angle difference (pitch) error of 0,2 mm and compensations by the correction greatly enhance the accuracy in the *Y*-axis pitch error that has been improved to 0,04 mm. Anthony [5, 6] proposed linear positioning errors using the laser interferometer in the vertical machining centre. The use of the Renishaw laser interferometer measurement system can calibrate angle errors in a three-axis CNC machine tool. Ibaraki S. et al. [7] employed a 2D space laser step-diagonal measurement method, referring to the use of Doppler laser interferometer combined with vector operations and sub-step diagonal measurement volume machine error. W. Ptaszyñski, et al. [8] employed XL-10 Renishaw interferometer measurement methods of investigation in straightness of 10 meter long guideways of a CNC machine. The 21 independent geometric errors of the machine can be fast calibrated. And the analysis of radar identification shooting sperm volume method presented a formula for calculating the degree to improve the installation error and quickly identify the errors that have been also verified by actual experimental reliability and validity.

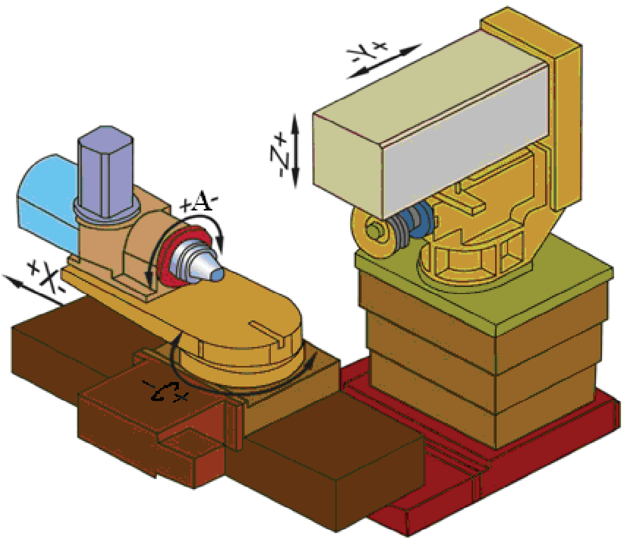


Figure 1 5-axis CNC tool grinder

In this study for the construction of linear axis and rotary axis measurement system in a 5-axis tool grinder, laser interferometer and rotary encoders have been employed by the spiral dynamic measurements. Selfdeveloped components include a measurement program and the module of error compensations so that the precision of machine tools can be improved. For experiments, a TG-5 Plus five-axis tool grinder with four flat knife blades for grinding has been used. The developed measurement system has been applied in the tool grinder and after the calibration some analyses about the influence of error compensation have been proposed. Fig. 1 illustrates the 5-axis tool grinder produced by the TOPWORK Company.

2 Definition of measuring dimensions

The end mill is the most frequently used tool e.g. side mill, step mill, groove mill and rough mill. The main parameters of an end mill have been shown in Fig 2. These geometrical angles are dependent on the processing material and will affect the cutting tool life and the roughness of the processed surface.

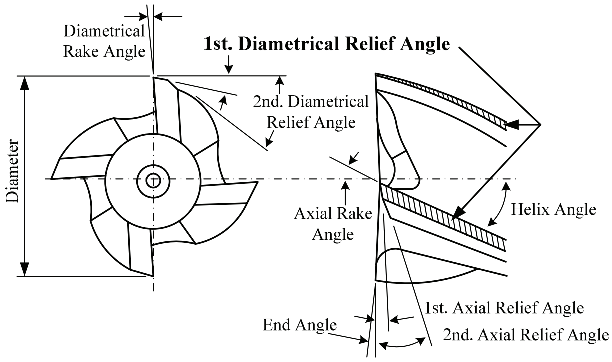
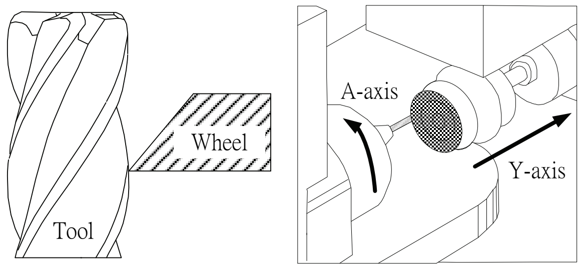


Figure 2 Parameters of an end mill

Concave relief angle is defined as the distance difference between the centres of wheel and cutting tool divided the radius of the cutting tool (Fig. 3). The linear axis (Y) and rotary axis (A) would be simultaneously driven at grinding concave relief angle (θ), as shown in Fig. 3. The definition of the helix angle (α) has been illustrated in Fig. 4. By the relationship between these parameters, it is evident that the position error of the linear axis (Y) and rotary axis (A) would lead to the error of concave relief angle. This investigation will be focused on the development of a measurement system for linear and rotary axis in the tool grinder, in order to determine the error values and compensate them in controller for the enhancement of the processing accuracy.



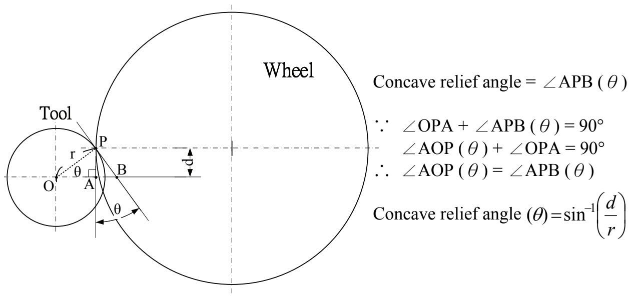


Figure 3 Concave relief angle

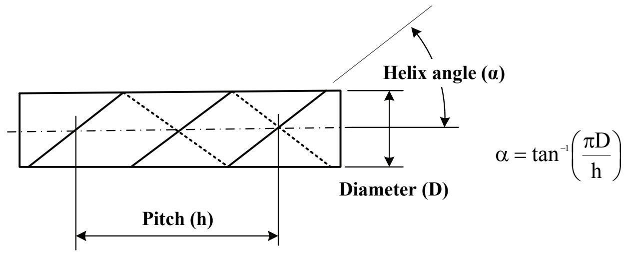


Figure 4 Helix angle

3 Measurement system

The frame diagram of the measurement signals in the developed system is schemed in Fig 5. Laser interferometer Renishaw RLE10 has been used for displacement measurement of Y-axis. From the interferometer two signals (sine and cosine) with phase difference of 90° will be gained and then connected to the counting cards. After the counting and direction verification, the displacement values will be transferred to measurement program. The experimental arrangement is shown in Fig. 6.

Ring encoder (Renishaw RESR150) is employed for the rotary indexing measurement. The configuration and installation are demonstrated in Fig. 7. In accordance with the optical design of the steel ring the encoder is fixed on a fixture and some fine-tunings for optical detection head must be carried out to achieve the optimal measurement performance of the encoder.

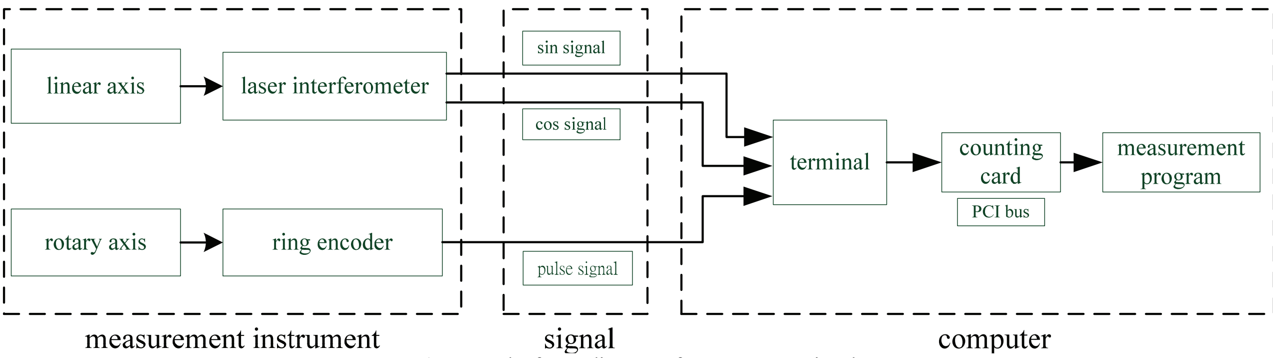


Figure 5 The frame diagram of measurement signals

The output signals of laser interferometer and ring encoder are transferred to computer by the counting card (PCI-1784U), the count values multiplied the resolution of the instrument and will reveal the displacement and angle values. Here the resolution of the laser interferometer is 20 nm and that of the ring encoder is 0,27 arcsec. That will be able to satisfy the measurement requirement of the tool grinders.

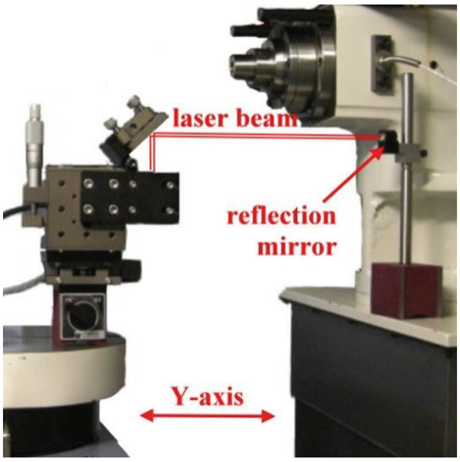


Figure 6 Linear axis (*Y*)

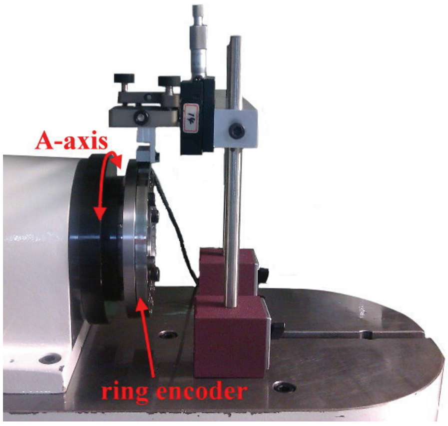


Figure 7 Rotary axis (*A*)

4 Experimental results

Linear axis positioning test is aimed to the *Y* axis positioning accuracy in TG-5 tool grinder. The *Y* axis travel range is 240 mm. The measuring interval is arranged at 10 mm. For rotary indexing test, the rotary axis *A* is utilized. Its measuring range is 360° and the measuring interval is 10°.

4.1 Linear axis

Fig. 8 indicates that for the *Y*-axis the forward positioning maximal error is less than 0,016 mm and the backward positioning maximal error is about 0,021 mm which also reveals the systematic positioning errors of the *Y*-axis, if there is no compensation. With the pitch and backlash error compensation, the errors will be significantly reduced to the range between –0,001 and 0,001 mm. The maximal backlash error is from 0,02 mm reduced to about 0,002 mm with the aid of compensation and the positioning accuracy has been distinctly enhanced.

4.2 Rotation axis

The rotary indexing test results for the *A*-axis are shown in Fig. 9. In the forward direction, the maximal indexing error is less than 0,01° and in the backward direction that is about 0,012°. After compensation, the maximal indexing errors have been reduced to 0,001 degrees and 0,004°. A maximal backlash error of about 0,006 occurs in the backward direction. Because only compensation for forward direction is available in the CNC controller, the errors in forward direction are usually lower than those in backward direction for which only backlash compensation can be offered.

4.3 Simultaneous measurement and analysis of the helix angle

Two-axis dynamical measurement for concave relief path of the cutting tools has been performed by the use of simulation software GUTS that generates the NC milling tool path programming. The end-mills have the following dimensions: diameter of 4 mm, 4 flutes, tool length of 20 mm and helix angle of 35°. Measurements in accordance with the detected cutting tools are designed to acquire the angles of the four edges respectively. Measurement experiments have been carried out in the conditions with and without compensations. Fig. 10 also shows that the compensation will be obviously beneficial for the minimization of processing errors.

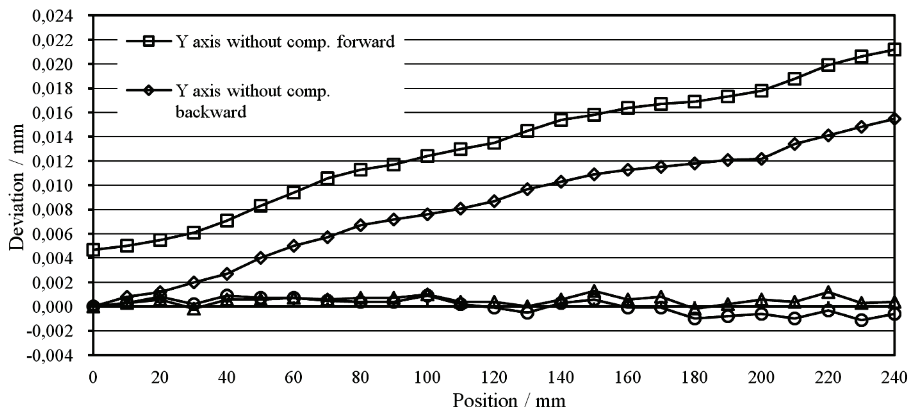


Figure 8 Error analysis of *Y* axis

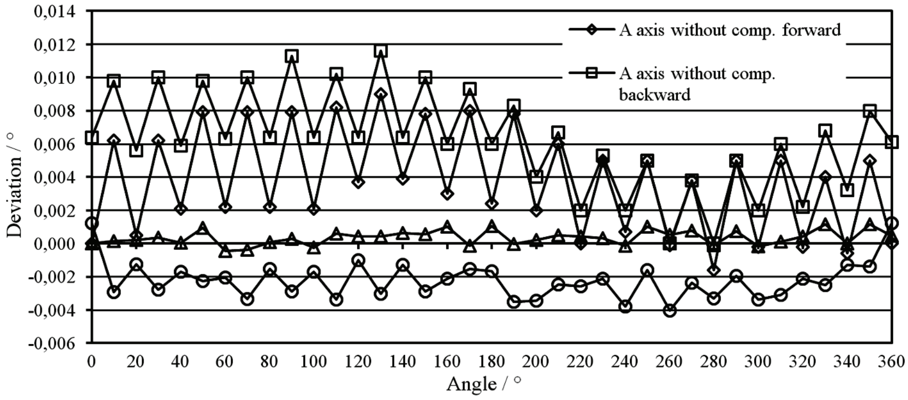


Figure 9 Error analysis of *A* axis

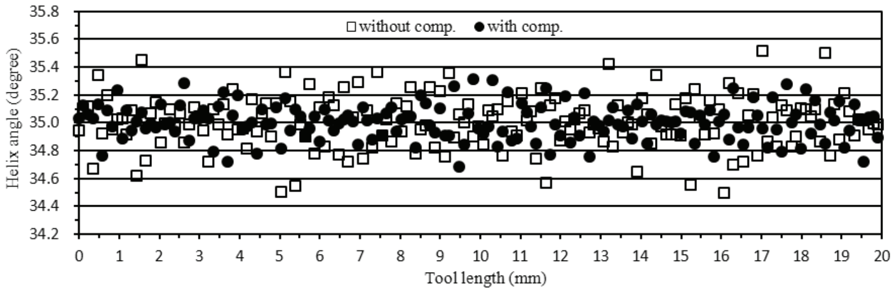


Figure 10 Error analysis of helix angle

For the verification of compensations in the *A*-axis and *Y*-axis, two experiments have been performed. At the first one, only for the *A*-axis, the compensation influence on the diameter of the cutting tools will be compared. The other method is to analyze the helix angles and compare the effect before and after the compensations of the *A*-axis and *Y*-axis. There are 10 cutting tools used as test objects which will be ground under the condition with and without compensations respectively. After their processing, the diameters and helix angles will be verified by the commercial measurement instrument Zoller genius3.

Table 1 The result of the *A* axis with and without compensation (in mm)

No	A axis without Compensation			A axis with Compensation		
	M 1	M 2	Average	M 1	M 2	Average
1	3,992	3,997	3,9945	3,982	3,984	3,9830
2	3,997	3,996	3,9965	3,983	3,981	3,9820
3	3,991	3,990	3,9905	3,984	3,983	3,9835
4	3,990	3,989	3,9895	3,983	3,981	3,9820
5	3,996	3,991	3,9935	3,981	3,984	3,9825
6	3,998	3,996	3,9970	3,981	3,982	3,9815
7	4,000	4,002	4,0001	3,984	3,981	3,9825
8	3,999	3,996	3,9975	3,980	3,981	3,9805
9	3,999	3,996	3,9975	3,980	3,982	3,9810
10	4,000	4,000	4,0000	3,980	3,982	3,9810
		Standard deviation:	0,00376		Standard deviation:	0,00096

Table 2 The result of the *Y* and *A* axis with and without compensation (in °)

No	Concave Relief without Compensation				Concave Relief with Compensation			
	M 1	M 2	M 3	M 4	M 1	M 2	M 3	M 4
1	34,90	34,83	34,82	34,76	34,84	34,79	34,74	34,89
2	34,84	34,77	35,03	34,85	34,88	34,70	34,80	34,95
3	34,94	34,92	35,06	34,94	34,79	34,81	34,86	34,79
4	34,91	34,93	34,97	35,04	34,87	34,87	34,78	34,86
5	34,69	34,90	34,93	35,01	34,77	34,79	34,76	34,81
6	34,74	34,76	35,01	34,84	34,75	34,85	34,82	34,83
7	34,78	34,85	35,06	34,76	34,88	34,88	34,78	34,87
8	34,81	34,79	35,04	34,82	34,83	34,83	34,88	34,76
9	34,86	34,82	34,94	34,86	34,81	34,81	34,81	34,91
10	34,74	34,94	34,92	34,80	34,78	34,78	34,83	34,92
Standard deviation:	0,0992				0,0536			

In Tab. 1, the measurement results of the diameter are listed. Here M1 and M2 mean cutting tools diameter processed under the cutting flute 0°, 180° and 90°, 270°. Under the processing conditions without compensation, the standard deviation (σ) is about 0,004 mm and that will be reduced to about 0,001 mm, if the compensation is performed. For general applications with the amount of 2σ, the improvement of processing precision will achieve 0,006 mm.

In Tab. 2, M1, M2, M3 and M4 denote the cutting flute at 0°, 90°, 180° and 270°. With the compensation of the *A*-axis and *Y*-axis, the standard deviation of helix angles has been improved to about 0,05° (σ). From the above results, the positive effect of compensation methods can be obviously verified.

5 Conclusion

The developed measurement system for linear and rotary axes in the tool grinder possesses the following features.

1. According to the measurement results, Figs. 8 and 9, the accuracy of the linear axis can be enhanced to 0,002 mm and that of the rotary axis to 0,011 degrees by the compensation method provided in the proposed system.
2. With the aid of compensating the rotary axis (*A*), the diameter precision has been improved 0,006 mm. By the compensation of the linear axis (*Y*) and the rotation axis (*A*), the standard deviation of the helix angle of the concave relief has enhanced 0,09 degrees.
3. In this investigation for tool grinder, the measurement system has integrated optical laser interferometer and ring encoder for simultaneous measurement of the linear axis and the rotary axis. The proposed system can be also utilized for the two-axis dynamic measurement (such as *XY*, *AX*, *AY*) in other machine tools for the verification of the multi-axis positioning precision.

6 References

[1] Kiridena, V. S. B.; Ferreira, P. M. Modeling and estimation of quasi-static machine-tool error. // Transactions of NAMRI/SME, 19, (1991), pp. 211-217.

[2] Kiridena, V. S. B.; Ferreira, P. M. Kinematic modeling of quasistatic errors of three-axis machining centers. // International Journal of Machine Tools & Manufacture, 34, (1994), pp. 85-100.

[3] Ferreira, P. M.; Liu, C. R. A contribution to the analysis and compensations of the geometric error of a machining center. // CIRP Annals-Manufacturing Technology, 35, (1986), pp. 259-262.

[4] Weikert, S. R-Test, a New Device for Accuracy Measurements on Five Axis Machine Tools. // CIRP Annals-Manufacturing Technology, 53, 1(2004), pp. 429-432.

[5] Anthony Chukwujekwu Okafor; Yalcin M. Ertekin. Vertical Machining Center accuracy characterization using laser interferometer Part 1: Linear positional errors. // Journal of Materials Processing Technology, 105, 3(2000), pp. 394-406.

[6] Okafor, A. C.; Ertekin, Y. M. Vertical Machining Center accuracy characterization using laser interferometer Part 2: Angular errors. // Journal of Materials Processing Technology, 105, (2000), pp. 407-420.

[7] Ibaraki, S.; Hata, T.; Matsubara, A. A new formulation of laser step-diagonal measurement-two-dimensional case. // Precision Engineering, 33, 1(2009), pp. 56–64.

[8] Ptaszyñski, W.; Gessner, A.; Frckowiak, P.; Staniek, R. Straightness measurement of large machine guideways. // Metallurgy, 50, (2011), pp. 281-284.

Authors' addresses

Yung-Cheng Wang
National Yunlin University of Science and Technology
Faculty of Mechanical Engineering
No. 123, University Rd., Section 3
640 Douliou, Yunlin, Taiwan

Chi-Hsiang Chen
National Formosa University
Institute of Mechanical and Electro-MechanicalEngineering
No. 64, Wunhua Rd.
632 Huwei, Yunlin, Taiwan
e-mail: explorer5270@gmail.com

Bean-Yin Lee
National Formosa University
Department of Mechanical and Computer-Aided Engineering
No. 64, Wunhua Rd.
632 Huwei, Yunlin, Taiwan

Tun-Hao Liang
National Formosa University
Department of Mechanical and Computer-Aided Engineering
No. 64, Wunhua Rd.
632 Huwei, Yunlin, Taiwan

Te-Shing Chung
National Yunlin University of Science and Technology
Faculty of Mechanical Engineering
No. 123, University Rd., Section 3
640 Douliou, Yunlin, Taiwan