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LINEAR MOTION ERROR EVALUATION OF OPEN-LOOP CNC MILLING USING A LASER INTERFEROMETER

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Abstract: The usage of computerised numerical control (CNC) machines requires accuracy verification to ensure the high accuracy of the processed products. This paper introduces an accuracy verification method of an open-loop CNC milling machine using a fringe counting of He–Ne laser interferometry to evaluate the best possible accuracy and functionality. The linear motion accuracy of open-loop CNC milling was evaluated based on the number of pulses from the controller against the actual displacement measured by the He–Ne fringe-counting method. Interval distances between two pulses are also precisely measured using the He–Ne interferometry. The linear motion error and controller error can be simultaneously evaluated in sub-micro accuracy. The linear positioning error due to the micro-stepping driver accuracy of the mini-CNC milling machine was measured with the expanded uncertainty of measurement and was estimated at 240 nm. The experimental results show that linear motion error of the open-loop CNC milling can reach up to 50 μm for 200 mm translation length.

Key words: accuracy, micro-stepping driver, CNC, milling, machine, interferometry, open loop

1. INTRODUCTION

Computerised numerical control (CNC) has been widely used in the manufacturing industry given its advantages of precision, accuracy, cutting productivity, and complexity of work that can be handled. CNC has a crucial role in the manufacturing industries nowadays [1-3]. Since the operation and maintenance of a CNC machine requires a highly skilled operator, numerous universities worldwide have developed several computer numerical machine courses to fulfil the demand for highly skilled human resources in the metal processing industry. Moreover, the computer numerical control course can also be used to introduce a control system and manufacturing technology teaching aid for elementary and junior high school students [4-6].

For low-cost digital manufacturing and educational purposes, a small open-loop controlled CNC milling machine, with relatively simpler instrumentation and cheaper than the close-loop types, can be a suitable choice. Since an open loop is not equipped with a feedback system such as a linear encoder, an open-loop control system is considered cheaper than a closed-loop system [4]. However, the customised milling machine has several limitations, such as a lack of components' dimension accuracy, inappropriate components' interaction, low rigidity and control system problems influencing the cutting performance. Korkut and Donertas stated that the machining performance is influenced by several parameters such as the cutting speed, feed rate, depth of cut and design of the machine [7]. Furthermore, Zmarzly reported that the influence of cutting parameters, especially cutting speed, on the surface quality is considered significant [8]. In order to provide the best possible accuracy and functionality, the accuracy of the developed open-loop CNC milling machine must first be verified.

The verification of an open-loop CNC milling machine can be started from geometric accuracy, which is one of the important evaluated parameters and depends on the translation accuracy of the axes and cutting accuracy [9-11]. The geometric accuracy of machine tools can be divided into two groups, single-axis geometric accuracy and geometric accuracy between axes [12]. The single-axis geometry accuracy can be determined by evaluating the single-axis translation errors. Hence, the potential machining error can be reduced, or an error compensation can be performed using the evaluation data.

The international standard of CNC accuracy evaluation is detailed in ISO 230, which consists of an accurate measurement without the stated load [13,14]. ISO 10791 also specifies several families of tests for machining centres with a horizontal spindle, standing alone or integrated into flexible manufacturing systems [15,16]. In general, linear positioning errors of mini-CNC milling machines can be identified by measuring the table displacement using laser interferometry, dial testers, ball-bars and other measuring devices [17,18]. However, a detailed correlation between the motor controller and actual translation still cannot be easily obtained. A method to simultaneously obtain the correlation of some parameters, such as motor, motor driver, controller, software, and translation table, is required to be developed for the small CNC milling machine with an open-loop control system.

Therefore, this paper proposes an experimental method to evaluate the correlation between the displacement and signal (pulse) of a micro-stepping motor driver using a He–Ne fringe-counting method for a small CNC milling machine. The paper first discusses the methodology, including the experimental setup and the test rig. Then, the effectiveness of the method and the accuracy of the calculation are discussed in the results and discussion sections.

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2. METHODOLOGY

In this research, the open-loop CNC milling has been built in our laboratory [19]. The translation length of the open-loop CNC milling table is defined by the CNC part program (G-Code) that controls the number of pulses given to the motor controller (Fig. 1). Some error sources that contribute to the total error are shown in Fig. 2. The first error is the error due to the interface problem (error 1). The second error is the error due to the motor controller (error 2). Errors 3 and 4 are transmission errors and motion errors caused by an imperfect guide system, respectively.

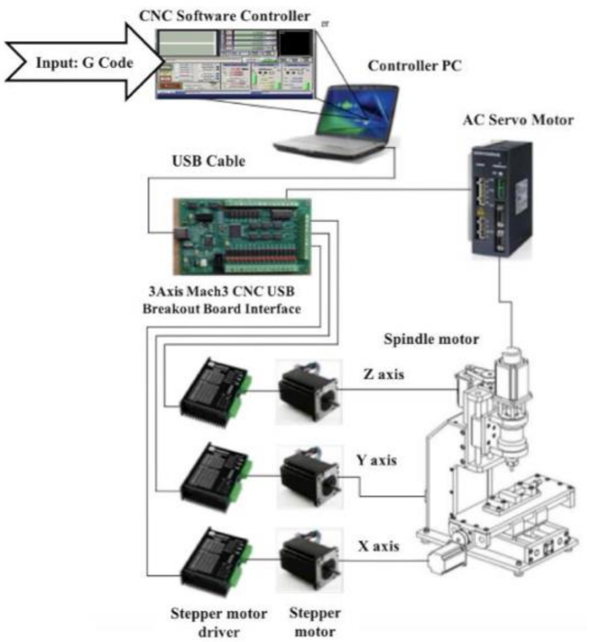

Fig. 1. Schematic diagram of an open-loop mini-CNC milling

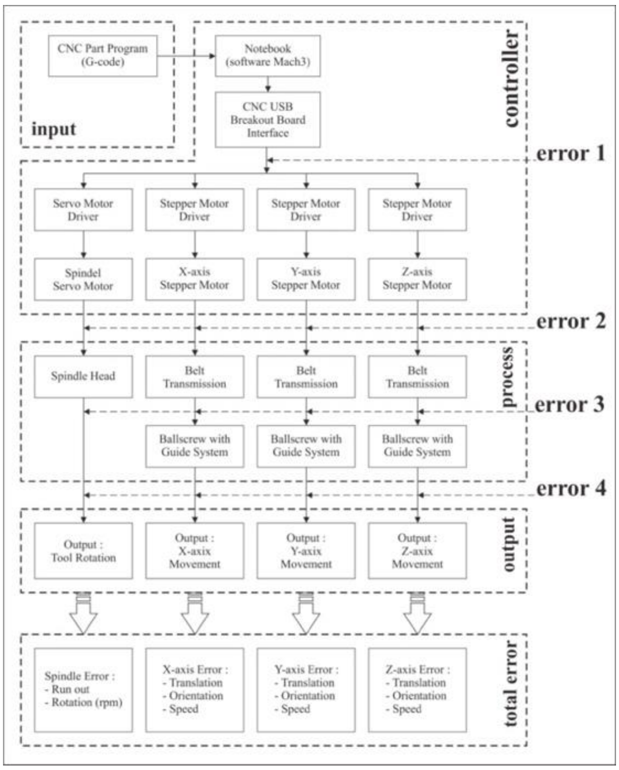

Fig. 2. Map of error sources in the open-loop CNC milling machine

There are six types of motion errors in a single axis milling machine table, grouped as either linear motion errors or rotational motion errors, as shown in Fig. 3. Linear motion errors consist of positioning errors (E_{XX}), vertical straightness errors (E_{ZX}) and horizontal straightness errors (E_{YX}). Rotational motion errors consist of pitch angular errors (E_{BX}), yaw angular errors (E_{CX}) and roll angular errors (E_{AX}). In this research, the method of evaluating the linear positioning error due to the micro-stepping driver accuracy of the mini-CNC milling machine consisted of applying fringe-counting He–Ne laser interferometry to measure the error displacement in E_{XX} direction. The translation of mini-CNC milling machines was compared with the translation measured by He-Ne laser interferometry [20]. Therefore, the correlation between the electric pulse that controls the stepper motor, and the real translation of the CNC table can be evaluated.

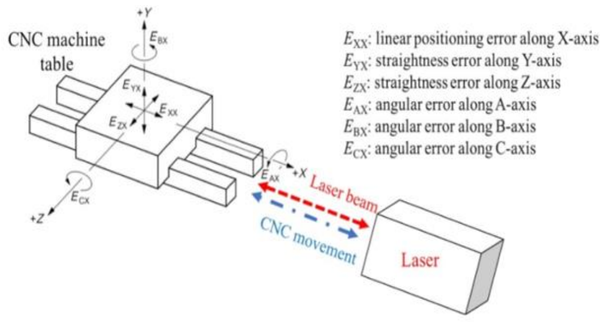

Fig. 3. Method for evaluating the accuracy of the CNC machine using laser interferometry by measuring the positioning error

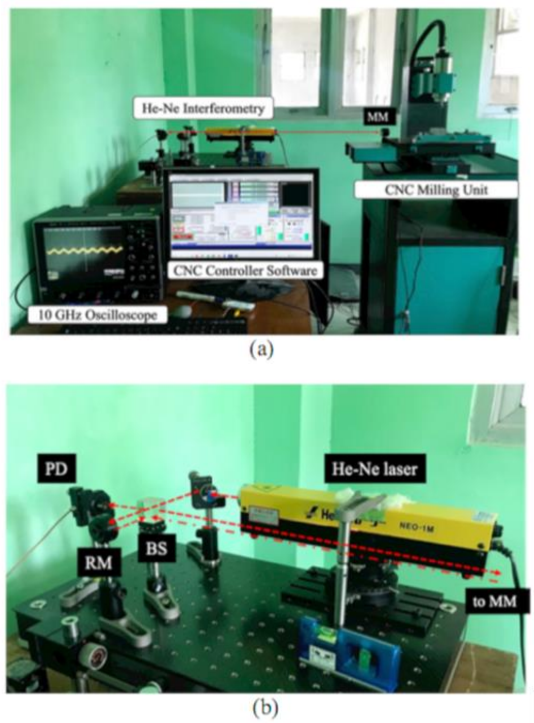

Fig. 4. Setup of evaluation of a mini-CNC milling machine using He–Ne interferometry, consisting of (a) the He–Ne interferometer and (b) retroreflector on the table of the mini-CNC [20]

In this study, the effect of the micro-stepping motor driver on the accuracy of the mini-CNC milling machine was evaluated. The CNC milling machine used in the experiment is a vertical fixed bed type developed in our laboratory (Fig 1). The configuration of

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mechanical and electrical parts is shown in the schematic diagram of the open-looped CNC control system. It has a travel distance of 200 mm, 150 mm and 120 mm in X, Y and Z axes, respectively. The experimental setup consists of He–Ne interferometry, an open-loop mini-CNC milling unit and an oscilloscope, as shown in Fig. 4(a).

To minimise the geometrical error, the configuration of beam laser was set carefully, such that the laser beam was in alignment with the path of motion followed by the machine [Figs. 3 and 4(b)]. The open-loop CNC milling machine consists of three motor steppers controlled by micro-stepping drivers (M542, Leadshine Technology Co., Ltd.).

The G-codes are interpreted by Mach3 CNC software to control the stepper motor using an electric pulse generated by a micro-stepping driver. The micro-stepping driver divides one step of a stepper motor (1.8° or 1/200 revolution) into 25 micro-steps. Hence, the total pulses delivered to the motor stepper is 5,000 pulses/revolution. The milling table is driven by a double start ball-screw with 10 mm lead (5 mm effective pitch).
The distance between two pulses (L_P) is calculated as 1 μm by using Eq. (1), as follows:

$$L_p = \frac{P}{i_{ms} \times i_r} \quad (1)$$

where P is 5,000 μm, which is the effective pitch; i_{ms} is 25, which is the number of steps constituting one step of a stepper motor, 25 thus being the micro-step resolution (the number of micro-steps per motor stepper step); and i_r is 200, which is the number of steps per revolution of the motor stepper.

The translation of the CNC table was measured using unstabilised He–Ne fringe-counting interferometry. In this method, the unstabilised He–Ne laser beam from source (NEO-1M, Neoark) with a wavelength of 632.9908 nm incident to the beam splitter BS (BS004, Thorlabs) is divided by two, where one beam is incident to a reference mirror (RM), and another beam is incident to the moving retroreflector (MM) on the table of the mini-CNC milling, as shown in Fig. 4(b). Finally, the reflection beam from MM and RM was detected by a photodetector PD (SM1PD1, Thorlabs), and the fringe pattern was observed by a 10 GHz oscilloscope (Wave Runner 64Xi-A, LeCroy). The fringe-counting method has been widely used to measure the travelled distance [18]. To calculate the displacement length by He–Ne laser using the fringe-counting method, the total translation was calculated by Eq. (2):

$$d = \frac{\lambda \times i}{2n} \quad (2)$$

where d is the translation length in μm, λ is the wavelength (0.6329908 μm) of the unstabilised He–Ne laser in a vacuum [20, 21], i is the number of fringes recorded and n is the refractive index calculated by Ciddor's equation [23]. The measurement using wavelength is influenced by the refractive index, where the refractive index is also influenced by the medium [24-26].

The fractional uncertainty assigned to the vacuum wavelength of the unstabilised He–Ne laser is 1.5×10^{-6} (relative standard uncertainty) [21]. In order to simultaneously obtain the interference signal and pulse from the motor driver, the data was automatically recorded 2 s after the table moved to the designed positioned. The interference fringes and pulses were recorded by an oscilloscope with a 210 MS/s sampling rate. The data from the oscilloscope was analysed using an in-house program developed using Python to obtain the distance between pulses. Since the oscilloscope's memory was limited, evaluation of longer translation was also performed using the commercial laser measuring system Renishaw XL80 to obtain the error trend.

3. RESULTS AND DISCUSSION

Data of electric pulses are sorted to obtain each peak, as seen in Fig. 5, where the first pulse is set as a reference pulse. Afterward, relative distances from the reference pulse to the further pulses are calculated by counting the number of He–Ne fringes (integer and fractional parts). The electric pulses and He–Ne interference fringes provide detailed correlation between the micro-stepping driver and actual translation length. From Eqs (1) and (2), we ascertain that the ideal number of interference fringes between two pulses (i) in a vacuum is 3.16, because ideally, d = L_P = 1 μm. However, the number of He–Ne fringes between two pulses fluctuated based on the experimental data.

This fluctuation is considered to be caused primarily by the linear motion error, rather than changes in environmental conditions, since the measurement room was well controlled at 23 ± 0.5 °C and <70% humidity Maintaining humidity and temperature at an optimal level is important because controlled environmental conditions are necessary to rule out fluctuations caused by extrinsic causes [22]. As the second consideration, the fluctuation is caused by the accuracy of the micro-stepping driver in dividing one step of the stepper motor into 25 steps. In order to evaluate the effect of this fluctuation, the total number of pulses (i_p) were counted from the designed start point to the designed endpoint. From Eq. (1), the theoretical translation length in μm (L) is calculated as follows:

$$L = i_p \times L_p \quad (3)$$

From Eqs (2) and (3), the total translation error in m (E) can be calculated as

$$E = L - d = (i_p \times L_p) - \left(\frac{\lambda \times i}{2n}\right) \quad (4)$$

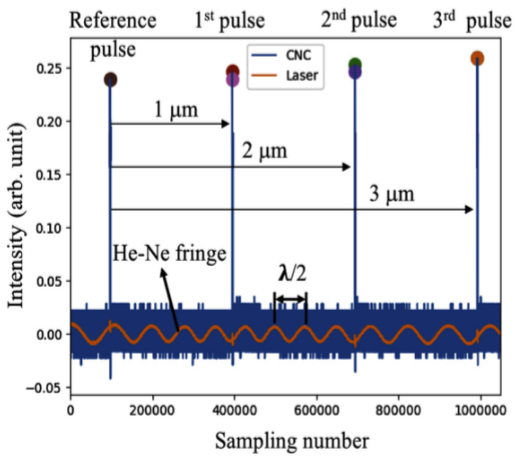

Fig. 5. The calculation result shows the correlation between pulse and distance

The data in Fig. 5 was calculated to obtain the actual distance between two pulses. The distance from the reference pulse to the second pulses (L_{P1}) was calculated as 0.819 μm, which differs by 181 nm from the theoretical value (1 μm). Based on 50 data of the distance measurement between two pulses, the average error from theoretical values was 70 nm, with a standard deviation of 170 nm. From this experiment, the maximum error of the micro-stepping driver can be estimated at about 170 nm. Due to the memory limitation of the oscilloscope in recording the data, only translation lengths up to 0.2 mm were evaluated using the proposed method, as shown in Fig 6. The result shows that the translation error is due to the fact that micro-stepping drivers linearly increase proportionally to the translation length. However, this data falls too short of predicting the error of longer translation. Therefore, the evaluation of longer translation was performed using the commercial laser measuring system Renishaw XL80, where the sampling point was taken every 5 mm. The distance between two pulses cannot be evaluated using Renishaw XL80 due to the limitation of the Renishaw software development kit (SDK) that only allows sampling points up to 10 sampling/s.

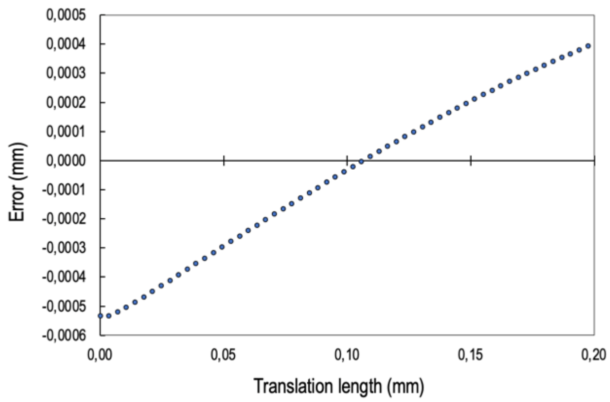

Fig. 6. The translation error of the open-loop CNC milling measured by the He–Ne fringe-counting method

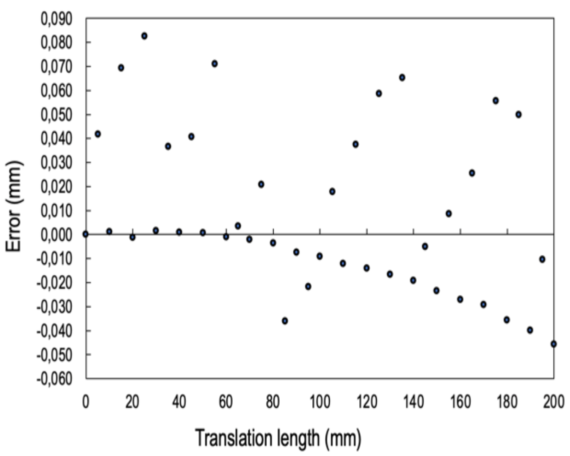

Fig. 7. The experimental result of long-distance translation using Renishaw XL80

The measurement using Renishaw XL80 shows that translation error increases until 30 mm translation length and then decreases to minus direction. The trend line in Fig. 7 shows that the error up to 200 mm translation length is about 50 µm. This error is considered as the error of the carriage table (error 4). From Fig. 7, we observe that there is a random error of about 85 µm, which could be attributed to problems associated with the transmission, mechanical, software or other aspects as causative factors. In the measurement of the table travel (i.e. CNC milling table), the periodic error, such as errors caused by the pitch of the ball-screw and pitch of linear or rotating scales, was wrecked [7]. The effect of motion between elements involved in the construction of machines is one of the most important errors that need to be considered [27]

From the experimental results obtained using the He–Ne fringe-counting method and the commercial length measuring system Renishaw XL80, we derive several observations, as follows: The measurement system should have at least ¼ resolution of the measurand, or its maximum error should not exceed one-quarter of the resolution of the measurand. The He–Ne fringe-counting method achieved a measurement standard deviation of 170 nm. Therefore, it is considered enough to be used in evaluating the micro-stepping driver with a 1 µm resolution. Based on the experimental data, we can consider that the error contribution of the micro-stepping driver to overall error is low. The He–Ne fringe-counting method can only measure short translation, but this method can be applied for longer translation length by adding a data acquisition system to obtain longer data.

The uncertainty budget of measurement up to 0.2 mm using the proposed method is shown in Tab. 1. The standard deviation of 170 nm, obtained from 50 repeated measurements, contributes 24 nm towards standard uncertainty. The uncertainty of distance measurement between two pulses is influenced by the accuracy of the fringe-counting method, which depends on the refractive index of air, wavelength and length.

The geometrical error attributable to imperfect alignment is estimated to contribute 100 nm towards standard uncertainty. Since the measurement room was well controlled at 23 ± 0.5 °C and <70% humidity, it is estimated that temperature fluctuations contribute towards standard uncertainty only by 5 nm. The number of pulses from the micro-stepping motor driver has been estimated to contribute to the standard uncertainty of 50 nm. The combined uncertainty is calculated to be 120 nm. Hence, the expanded uncertainty of the measurement is estimated at about 240 nm with k = 2.

Tab. 1. Uncertainty budget of the fringe-counting method

Uncertainty component	Source	Uncertainty contribution (nm)
u_c (L_d)	Distance between two pulses	
u (λ)	(He–Ne wavelength)	0.3
u (i)	(Number of waves)	32
u (n)	(Refractive index)	6
u (L_p)	Repeatability	24
u (i_p)	Number of pulses	50
u (G)	Geometrical error	100
u (L_t)	Temperature	5
Combined standard uncertainty (u_c)		120
Expanded uncertainty (k = 2)		240

The experiment allowed us to evaluate the linear positioning error attributable to the micro-stepping driver accuracy of the mini-CNC milling machine, and the expanded uncertainty of measurement was estimated at about 240 nm. This research is slightly different from the study of Begović et al [17]. Their research shows the results of linear displacement error measurement and indicates that as a consequence of increasing the lengths from 400 mm to 800 mm, error increases to a maximum of 140 µm

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while using commercial CNC. It is considered to reduce the error by re-arranging the interferometer to minimise the dead-path error. The linear translation accuracy of the open loop milling machine has been evaluated using Renishaw XL 80, and the results show that the error up to 200 mm translation length was about 50 µm. From the specification of Renishaw XL, linear measurement accuracy is an assured ±0.5 ppm. For education purposes, this machine is quite promising for use in real applications. Norhadi and Tarng stated that the open-loop system for CNC milling has shown good performance but is limited to use only in non-precise machining [4].

However, further improvement to reduce other errors such as transmission error and motion error caused by imperfect guide systems is highly demanded. The error compensation mechanism maybe good choices to be added. Xu and Dai stated that the error compensation method can be used to improve machining precision [11]. In brief, the accuracy of the micro-stepping driver motion is one of the important factors that affect the linier positioning of the CNC table, and thus warrants further consideration. Further accuracy evaluation such as cutting accuracy, the effect of cutting speed and feed rate and other parameters are considered possible future works.

4. CONCLUSIONS

An open-loop controlled CNC milling machine has been developed for low-cost digital manufacturing and educational purposes. The CNC with an open-loop control system is considered more suitable for educational purposes in terms of a lower price than a closed-loop system. An experimental method was proposed to evaluate the accuracy of an open-loop mini-CNC milling machine using the He–Ne fringe counting. The correlation between the translation error and the accuracy of the motor controller has been investigated. Using fringe counting He–Ne laser, the accuracy of the micro-stepping driver could be precisely evaluated by measuring the distance between two electric pulses. Linear motion error, especially the translation error up to 0.2 mm, was measured with the expanded uncertainty of 240 nm. The longer translation up to 200 mm was measured in order to obtain the overall accuracy of the open-loop CNC milling machine by using the commercial laser measuring system Renishaw XL80. The experiment shows that the linear motion error of the open-loop CNC milling can reach up to 50 µm for 200 mm translation length. From the perspective of educational requirements, the model of machine discussed in the present research offers promising results in terms of good machine design. Simulation to find the correlation between the displacement value for pulses of micro-stepping driver and error for longer displacement is considered as a candidate for future work. Further accuracy evaluation such as cutting accuracy, the effect of cutting speed and feed rate and other parameters are also considered as candidates for future works.

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