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A Comparative Study: The Precision of CNC Machines Using a Sliding Mode Controller (SMC) and a Wi-Fi ESP32

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ABSTRACT

Computerized numerical control (CNC) is one example of advances in automated machine technology. CNC can fulfil high precision and complex product specifications. Industrial CNC milling is still expensive regarding the hardware and software required to operate it. As a result, CNC milling machines are only used by large companies, with only a few mid-sized industries using them. It makes it impossible for medium enterprises to compete with large industries in terms of quality and output. This research aims to develop a CNC that uses an offline Wi-Fi controller based on ESP32 as an application that supports CNC machine work processes for use in small and medium enterprises. In an experiment, the precision of a CNC milling machine equipped with a sliding mode controller (SMC) controller was compared with that of a CNC machine equipped with an ESP-32 Wi-Fi controller. The CNC milling process with SMC control exceeds the tolerance limits in three dimensions based on the results of ten tests, namely length, width, and height or depth. Six values, two in each dimension of length, width, and height or depth, exceeded tolerance limits due to the CNC milling machine's ESP32 Wi-Fi control. Therefore, the CNC with SMC control is more accurate than the ESP32 Wi-Fi control because there are fewer failures with the former. This research has been carried out and provides input for the implementation of SMC, which can be considered in the CNC milling process.

Keywords: *Computerized numerical control, Experimental study, Sliding mode controller, ESP32 Wi-Fi*

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1. INTRODUCTION

Machining involves the coordinated motion of multiple axes in rotational and linear directions. A central unit known as the computer numerical control (CNC) integrates the electronically controlled signals to follow a predefined sequence of operations within a workpiece smoothly. Tool paths are generated beforehand depending on the desired final product [1]. A natural control technique is used by the sliding mode controller (SMC), which was initially conceived by Utkin [2]. his strategy is chosen to counteract the influences of disturbances and uncertainties connected with the model parameters. A sliding mode controller (SMC) is a method of control that can accommodate disruptive system changes without affecting the system's performance [3]. The SMC is a method that offers a vast array of modeling options. Sliding mode control is a very well, one-of-a-kind innovation for a discontinuous control method that has been investigated in-depth by numerous authors in numerous academic publications. The SMC structure consists of a primary component that corrects the error signal by directing it along the desired trajectory and a secondary part that maintains the movement. SMC optimally serves position control of DC motors. It is suitable for controlling switched-controlled processes, such as power electronics devices, and a nonempty class of mechanical and electromechanical systems, robots, motors, and satellites [4]. The SMC was selected due to the robustness of the control system, which anticipated solving the problem of the DC motor's parameters fluctuating due to loading. It has an intriguing type of control that can aid problem-solving and expressing uncertainty [5]. It has been discovered that combining PD control and SMC in a robotic system can significantly reduce the number of tracking errors [6].

Moreover, it has been found that an SMC controller with a nonlinear sliding surface can improve the contouring accuracy of machining [7]. One design of SMC consists of two components: a switching control and an equivalent control. The specification of the sliding surface was used to derive the equivalent control and combined with the switching control to cause the system to slide along the surface. As a result of the generally discontinuous implementation of switching control, control signals frequently exhibit undesirable chattering [8]. A control system called integral sliding mode control (ISMC), which employs critical control action, has been developed to address this issue [9]. In order to achieve particularly dynamic performance, the system's dynamics are modified so that it slides along a predetermined sliding surface. It was accomplished by integrating disturbance estimations and required control actions into the controller, matching axial dynamics, and refining contouring precision. It was accomplished and implemented by applying the same sliding surface model to the X and Y axes [9] [10]. ISMC has also been seen in the rapid servo diamond-turning process [11].

In order to improve the accuracy of contouring in generic multi-axis motion systems, feedback controllers should be built to match the dynamic characteristics of all axes [12]. It was possible by coordinating the dynamics of each axis. Poo et al. highlighted the importance of dynamics matching in their study on contouring applications [13]. They established that if the axial dynamics were fully matched for linear contours, the contour error would be zero. Only when the axial dynamics are precisely aligned is this true. In the case of circular contours, having completely matched axial dynamics will generate a steady-state circular contour that, depending on the angular velocity, will have a radius that is either larger or lower than the intended radius. Yeh and Hsu [14] have designed a perfectly matched feedback controller, abbreviated as PMFBC, for use with multi-axis motion systems. After determining the different axial dynamics, feedback controllers were constructed to achieve a perfect match between the controllers' dynamics and outputs. However, because there will always be errors in the models utilized, it is impossible to attain exactly matched dynamics. Mubita et al. [15] have shown that matching the loop's gains is more crucial than matching the loop's time constants.

Extensive research has been conducted and evaluated on the CNC process with the SMC approach. As far as the authors can tell from references in published articles, there have been no experimental studies comparing the precision of a CNC milling machine controlled by SMC to one controlled by ESP32 Wi-Fi. The hardware and software required to operate a CNC milling machine are still expensive in the business world. The hardware and software required to operate a CNC milling machine remain expensive in the industry. Consequently, a handful of middle and low-level businesses utilized CNC milling machines. It renders medium-sized industries incapable of competing with large industries in terms of output, effectiveness, and velocity. The design and implementation of a CNC router machine and completed using an offline controller based on ESP32 Wi-Fi to support the CNC router machine's work process. This CNC router will assist the middle and lower industries due to its affordable hardware and software costs. The ESP32 is a hardware microcontroller that includes Wi-Fi and Bluetooth modules and up to 4 MB of memory. ESP32 has several advantages over other microcontrollers, with built-in Wi-Fi and Bluetooth modules facilitating Internet connectivity. IoT projects require Internet connectivity, and the GPIO pin on the ESP32 can be used and optimized for various purposes. Figure 1 shows the ESP32 microcontroller hardware used.

2. RESEARCH METHODOLOGY

2.1. Material and devices

The material utilized in this investigation is a 31.75 mm in diameter Teflon® rod (PTFE). Polytetrafluoroethylene is a solid fluorocarbon because it is a high-molecular-weight polymer composed entirely of carbon and fluorine. Due to fluorine's weak electric polarization, fluorocarbons exhibit negligible dispersion forces, which renders PTFE impermeable. Neither water nor chemicals containing water can wet PTFE. PTFE has one of the lowest resistivities of solid materials. This design evaluation will determine the accuracy of this device, which has a tolerance of 0.05 mm. In this investigation, the test object had a square geometry with dimensions of 30 mm by 30 mm by 5 mm. The milling procedure utilizes an end mill with a diameter of 6.0 mm. Mitutoyo digital calliper within 0.01 mm tolerance and 200 mm of maximum range length has been selected and used for measuring the machining result. The geometry of the objects to be tested with CNC ESP32 Wi-Fi and CNC SMC is detailed below; computer-aided design (CAD) and computer-aided engineering (CAE) software were selected and implemented for the design. **Figure** 1 illustrates the geometric shape of the sample.

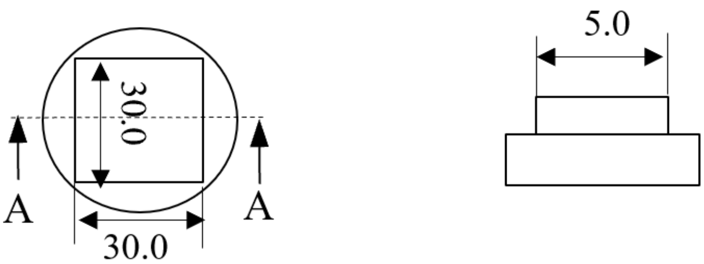


Figure 1. The geometry of the test specimen comprised of a Teflon® rod

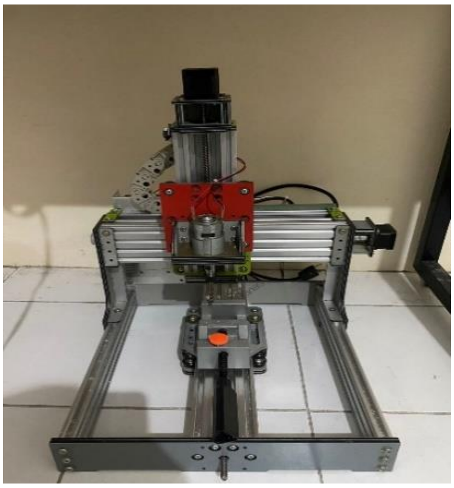
During testing, two CNC machines were controlled and operated using SMC and ESP32 Wi-Fi. Table 1 displays the parameters set and regulated on both machines to ensure that the machining process will produce precise results—comparative analysis and evaluation of the dimensional precision of the two machines' machining outcomes. In addition, there are I2C and SPI pins that facilitate communication. This ESP32 model features Wi-Fi connectivity. In August 1999, Interbrand Corporation was the first to use Wi-Fi commercially. Wi-Fi, also known as wireless fidelity, is a wireless connection compared to a mobile phone that enables users to transfer data quickly and securely through radio technology. In addition to connecting to the Internet, Wi-Fi can be used to create wireless networks within an organization. Wi-Fi was developed and created following the IEEE 802.11 standard. Figure 2 depicts the ESP32 Wi-Fi shows the ESP32 microcontroller hardware used in this study.

Figure 2. ESP32 Wi-Fi & Bluetooth compatible microcontroller [16]

The testing procedure utilized two CNC machines, both of which were controlled by the SMC and ESP32 Wi-Fi. Both machines have been configured with the parameters detailed in **Table** 1 to ensure that the machining process will yield precise results. The results of the machining performed by each of the two machines are compared in terms of their dimensional precision. For this study, the ESP32 Wi-Fi CNC machine and the SMC CNC machine, shown in the image of *Figure 3,* were used as platforms for experiments.

Table 1. Parameter selected for CNC-SMC and CNC ESP32 Wi-Fi Controlled.

Parameter	CNC ESP32 Wi-Fi	CNC SMC
Endmill Diameter (mm)	Ø 6	Endmill Ø 6
Strategi	Area clearance	Area clearance
feed per tooth (mm/tooth)	0.0032125	0,5
Max cut (mm)	0,5	0,5
First cut (mm)	0,5	0,5
spindle speeds *(rpm)*	400	400
Workpiece diameter (mm)	50	50
Machining time	± 10 minutes 32 seconds	± 9 minutes 19 seconds



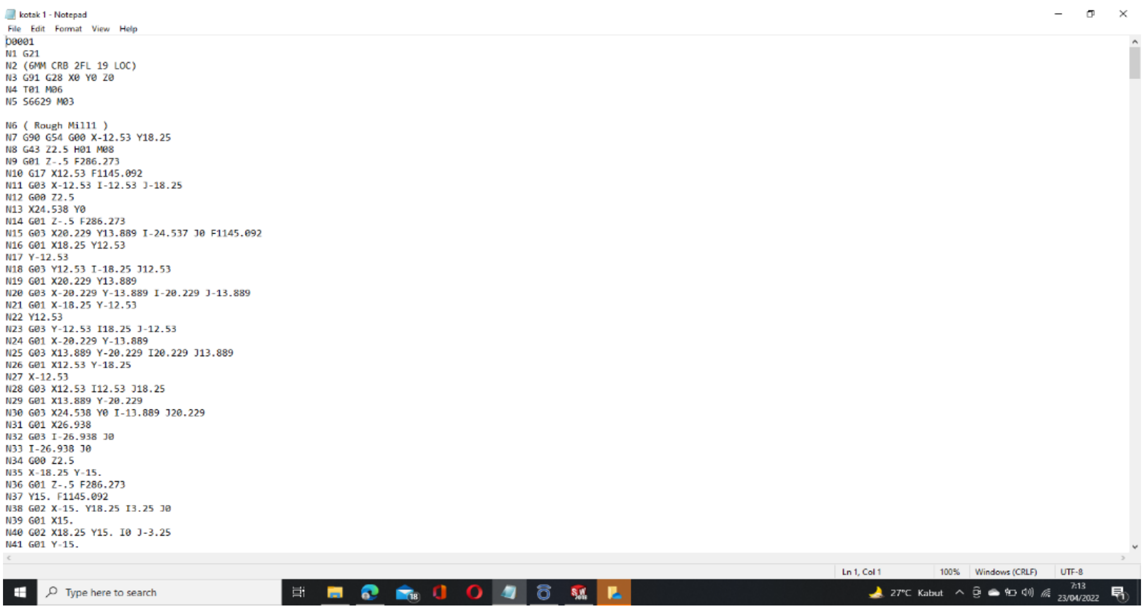
(a)

(b)

Figure 3. *CNC milling machines: SMC control (a) and Wi-Fi control (b)*

2.2. Desain machining sliding mode controller (SMC)

In order to generate G-code commands, this method simulates the machining process within the CAD and CAE software. The simulation phases were executed and controlled in a particular order in this investigation. In the initial stages, the process of designing the workpiece was performed and conducted, followed by the process of setting up the machine. The procedure for adapting to the layout of the workpiece employs mm units as the measurement standard. The material utilized by the CNC machine was determined and evaluated first by a set procedure conducted using a coordinate fixture system. It can determine which 0 value should be requested-provided on a CNC machine, followed by an edit definition executed to change the machine and the number of test objects consumed. The outcomes of the edit definition are then analyzed. After determining the depth of the end mill through the roughing procedure, click % on the initial cut and maximum cut. The minimum cut size should be 0.5 mm, while the maximum should also be 0.5 mm. The process tool was designed and provided to calculate the end mill size based on the size used. Generate operation plan is a function used to update any modified data. Before the machining process, a simulation was tried-implemented to ensure that the program would produce the desired dimensions of the workpiece. The purpose of this procedure is to guarantee that the program will generate accurate dimensions. Both the G-code creating process and the G-code saving process must be in text format so the CNC machine can read them, as shown in Figure 4.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N8 G43 Z2.5 H01 M08
N9 G01 Z-.5 F286.273
N10 G17 X12.53 F1145.092
N11 G03 X-12.53 I-12.53 J-18.25
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N30 G03 X24.538 Y0 I-13.889 J20.229
N31 G01 X26.938
N32 G03 I-26.938 J0
N33 I-26.938 J0
N34 G00 Z2.5
N35 X-18.25 Y-15.
N36 G01 Z-.5 F286.273
N37 Y15. F1145.092
N38 G02 X-15. Y18.25 I3.25 J0
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Figure 4. G-Code for sliding mode controller

2.3. Machining processes calculations

Cutting capability is an important indicator to evaluate the performance of a machine tool, such as whether it meets the qualifying condition of machine tool design for users' parts production [17]. The cutting capability test is the cutting load/heavy cutting test, and the MRR is a single number that enables evaluating it [18]. MRR is the volume of material removed per minute [18]. It is a direct indicator of how efficiently cutting and profitable are. The higher the cutting parameters, the higher the MRR. The cutting tool, spindle speed, modes of tool and workpiece, and cutting conditions are presented for chatter predicting. It was defined and determined as rules for ASME standards applied to the formulation of cutting tests to characterize the cutting performance of machining canters [19]. The machining procedure was divided-provided into several stages, including the such as, placing the workpiece in a vise-grip that serves as the base of the CNC machine, squeezing the workpiece so tightly that it cannot move, removing the workpiece from the vise-grip, put into operation the CNC machine; after setting the X 0, Y 0, and Z 0 points. It must be positioned correctly in the centre of the workpiece. Enter the G-Code file, then run the machine according to the instructions. After the machining process, the specimen pattern's form could be observed-correctly in the sample. Replace the end mill chisel and return the tool to its original position to complete the finishing process (X 0, Y 0, and Z 0).

Meters per minute is the standard units of measurement for cutting speed (*Vc*). The industry process necessitates that machining processes be completed quickly as possible. For the material to be appropriate, cutting speed would be used. If the cutting speed is too high, the cutting tool's edge erodes rapidly, and reconditioning the device is time-consuming. When the cutting speed becomes too slow, the wasted time during the machining operation results in low productivity. For efficient metal removal, high-speed steel cutting speeds are suggested and recommended. Depending on variables such as the machine's condition, the type of work material, and sand or hard spots in the metal, these speeds can be adjusted slightly—the cutting speed is calculated and implemented using equation 1.

$$V_c = \frac{\pi . D . n}{1000} \qquad (1)$$

Where *D* is the diameter of the workpiece in mm and *n* is the spindle speed in rpm. Based on the data presented in **Table** 1, where the workpiece diameter is 50 mm, and the spindle speed is 400 rpm, the calculated cutting speed is 62.8 mm/min. The distance intended to be represented by the feed rate is the distance travelled by the tool during a single spindle revolution. It is the rate the cutter introduced into the machine and expressed in terms of the distance travelled for each complete crank revolution. The distance travelled by the cutting tool during one spindle revolution is referred to as the feed rate. Another definition is "the velocity at which the cutter advanced against the workpiece," In terms of turning, the unit of measurement is millimeters' per revolution (MPR). The feed rate (mm/minutes) is formulae using equation 2.

$$V_f = n . f_z . Z \qquad (2)$$

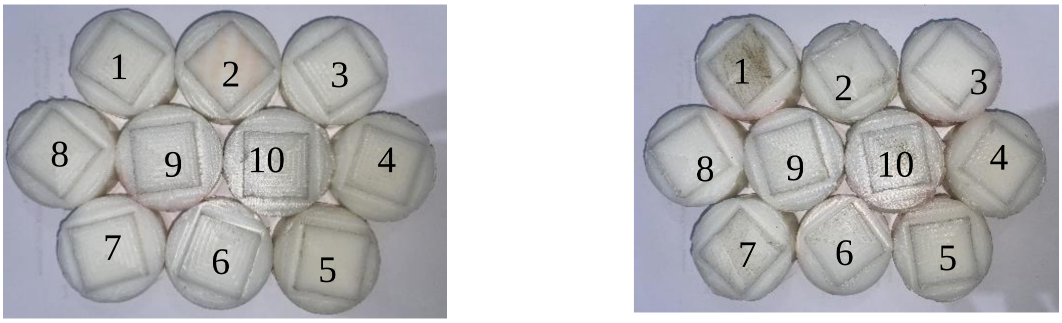
Where n is spindle speed in min.-1, $\boldsymbol{f_z}$ feed per tooth in mm/ tooth and $\boldsymbol{Z}$ is number of flutes. Based on on the data presented in table 2.1, where the feed per tooth is 0.031 mm/ tooth, number of lutes are 4 teeth, and the spindle speed is 4000 rpm, the calculated feed rate is 49.7 mm/min.

3. RESULTS AND DISCUSSIONS

3.1. Dimensional Analysis

This study compares the results of machining operations performed on CNC machines equipped with the ESP32 Wi-Fi controller and CNC machines equipped with the SMC controller. Teflon rods and a geometric design of a square of 50 mm diameter are selected and used to create workpieces. The dimensions of the workpieces are 30 mm in length, 30 mm in width, and 5 mm in height, with a tolerance of 0.5 mm applied to each specification. In order to produce the workpieces, the following operations comprise the stages of the machining procedure: In order to validate the parameters, run the same G Code tests on both machines. It is necessary to collect data on the machining process ten times on each machine to be objectively analyzed and compared to the data collected from the other machines. **Figure 5** represents each of the two machines that will be evaluated.

After the machining trial process was completed and controlled on a CNC machine equipped with ESP32 Wi-Fi control and SMC control, the outcome to be measured was the length, width, and height accuracy dimensions. The samples produced by the two machines were controlled and measured to ensure accuracy in two decimal places for their respective lengths, widths, and heights. The precision specifications are measured and determined by comparing the sample measurement data generated by the machining trial to the specifications for these three dimensions. The purpose of these comparisons is to conclude. The SMC control CNC machine machining sample contains one data point whose value exceeds the tolerance limit of 30.07 mm.



(a) (b)

Figure 5. CNC milling result: SMC control (a) and Wi-Fi control (b)

In contrast, the ESP 32 Wi-Fi control CNC machine machining sample contains three data points whose values exceed the tolerance limit by 29.92 mm, 30.09 mm, and 30.12 mm, respectively. Compared to the ESP 32 Wi-Fi control CNC machine's length, the SMC control CNC machine that performs machining is more precise in accordance with the specifications for measuring length. Figure 6 shows the comprehensive comparison of the sample length data obtained from the machining trial results.

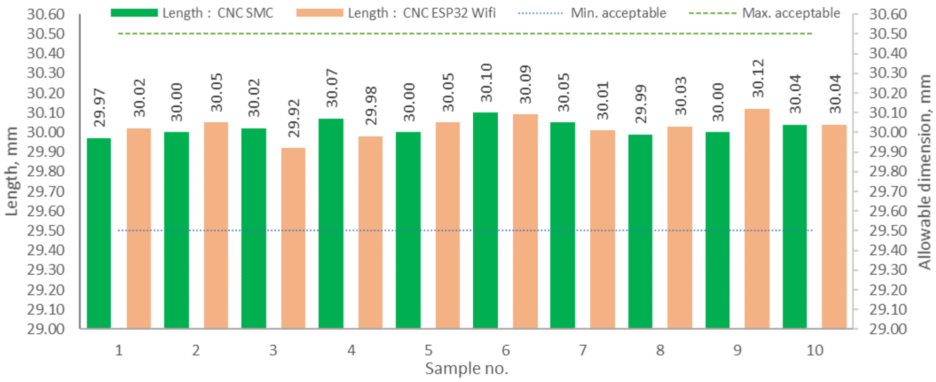


Figure 6. The length comparison results of SMC and Wi-Fi control

Meanwhile, for the measurement results of the width specifications, the sample results of the machining of the SMC control CNC machine were provided in Figure 7. The result showed that the 1-data value exceeded the tolerance limit, namely 30.09 mm. In contrast, in the sample results of the ESP32 Wi-Fi CNC control machine machining, three data points were found whose values were outside the tolerance limit, namely 29.9 mm, 30.09 mm, and 30.10 mm. Figure 7 compares the results of measuring the width specifications with greater precision and clarity.

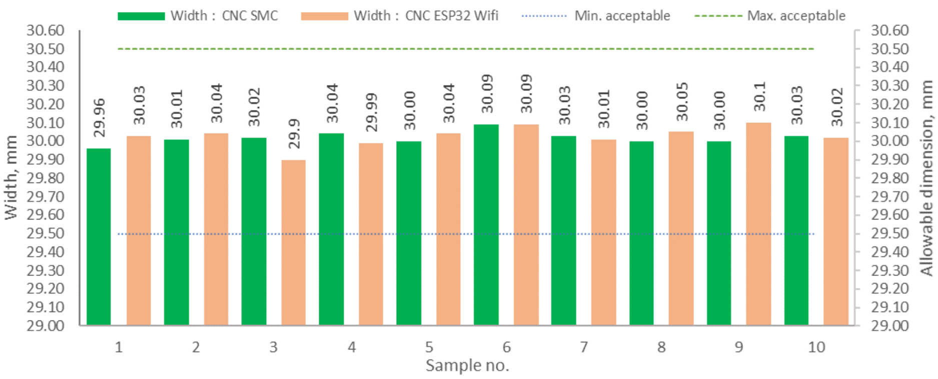


Figure 7. The width comparison results of SMC and Wi-Fi control

In the sample of machining results produced by the ESM control CNC machine, one data point exceeded the tolerance limit; its value was 5.08 mm. In contrast, the ESP32 Wi-Fi control CNC machine's sample of machining results revealed that four data points exceeded the tolerance limit. The tolerances measure 4.93 mm, 5.08 mm, 5.11 mm, and 5.06 mm, respectively; as a result, the results of SMC control CNC machine machining are more precise than ever. **Figure** 8 shows the data for the depth of the comparison result between CNCN SMC and Wi-Fi control.

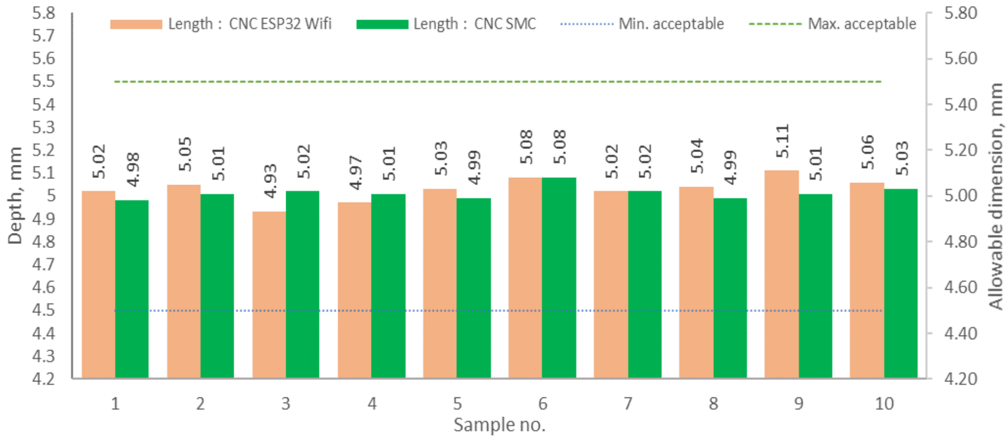


Figure 8. The depth comparison results of SMC and Wi-Fi control

Based on the findings, both methods can be used to carry out control systems on machine processes using CNC [20]. However, CNC with SMC is more accurate than Wi-Fi control. This is consistent with previous research, which indicates that the use of SMC in machining processes has a high degree of accuracy [6]. Another reason is that the internet network influences the use of the ESP32 Wi-Fi. To achieve high accuracy, you must have a strong internet network. A SMC pressurized on the translated version of the sliding surface from the beginning of the direction of travel has been displayed for controller design in drive system [21]. In order to reduce the frequency deviation and the integral of the absolute number of the shaft position, the shifting line has been shifted at a constant speed to meet the stator current's physical issue.

3.2. The confirmation analysis

Following the execution of machining trials on each machine, a process failure has been found and evaluated. There is just one occurrence of process failure data for each dimension, including length, width, and height, for the SMC-controlled CNC machine. For each specification, the CNC machine operated by ESP32 Wi-Fi contains two process failure data points. The results of CNC-controlled machining in three categories of minor process failures are shown in Table 2. However, the ESP32 Wi-Fi-controlled CNC machine's machining results include three process failures with minor categories and three process failures with significant categories [9]. In general, the precision of the machining test performed on the CNC machine controlled by SMC is superior to that of the CNC machine controlled by ESP32 Wi-Fi [7].

Table 2. Confirmation of the results of the experimental process's failure

No	Machining parameters	CNC SMC		CNC ESP32 Wi-Fi	
		Sample-4	Sample-6	Sample -6	Sample-9
1	Length (mm)	30.07	30.10	30.09	30.12
2	Width (mm)	30.04	30.09	30.09	30.1
3	Depth (mm)	5.01	5.08	5.08	5.11

4. CONCLUSIONS

A sliding mode controller and a Wi-Fi ESP32 control were used to successfully conduct an experimental study on the evaluation of the accuracy of a CNC lathe machine. Three values exceeded the tolerance limit during the milling machining process using CNC with SMC control, one in each of the dimensions of length, width, and height or depth. Six values exceeded the tolerance limit for milling machines controlled by CNC ESP32 Wi-Fi, two in each of the dimension's length, width, height, and depth.

One data point in the SMC control CNC machine machining sample exceeds the tolerance limit of 30.07 mm. Three data points in the ESP-32 Wi-Fi control CNC machine machining sample are 29.92 mm, 30.09 mm, and 30.12 mm out of tolerance. Meanwhile, for the width specification measurement results, one data point was found in the sample results of the machining of the SMC control CNC machine, namely 30.09 mm, whereas three data points were found in the sample results of the ESP32 Wi-Fi CNC control machine, namely 29.9 mm, 30.09 mm, and 30.10 mm. Based on these findings, it is possible to conclude that the CNC with the SMC control is more accurate than the CNC with the ESP32 Wi-Fi control because the failure rate is much lower. This research has been carried out and provides input for the recommendation SMC for CNC milling controlled.

AUTHOR'S DECLARATION

Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript.

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Availability of data and materials

All data are available from the authors.

Competing interests

The authors declare no competing interest.

REFERENCE

[1] L. Rubio Rodriguez, A. Ibeas, and L. E. Kollár, "On the sliding mode control for precision machining," *Mérnöki és Inform. Megoldások*, no. II., pp. 32–41, 2020, doi: 10.37775/eis.2020.2.4.

[2] V. I. Utkin, "Sliding Mode Control Design Principles and Applications to Electric Drives," *IEEE Trans. Ind. Electron.*, vol. 40, no. 1, pp. 23–36, 1993, doi: 10.1109/41.184818.

[3] J. Liu and X. Wang, *Advanced Sliding Mode Control for Mechanical Systems*. 2011. doi: 10.1007/978-3-642-20907-9.

[4] T. D. Modulation, *Sliding Mode Control: The Delta-Sigma Modulation Approach*, vol. 36, no. 3. 2016. doi: 10.1109/mcs.2016.2536079.

[5] V. I. Utkin, *Sliding Modes in Control and Optimization*. 1992. doi: 10.1007/978-3-642-84379-2.

[6] P. R. Ouyang, J. Acob, and V. Pano, "PD with sliding mode control for trajectory tracking of robotic system," *Robot. Comput. Integr. Manuf.*, vol. 30, no. 2, pp. 189–200, 2014, doi: 10.1016/j.rcim.2013.09.009.

[7] A. M. El Khalick, N. Uchiyama, and S. Sano, "Sliding mode contouring control design using nonlinear sliding surface for three-dimensional machining," *Int. J. Mach. Tools Manuf.*, vol. 65, pp. 8–14, 2013, doi: 10.1016/j.ijmachtools.2012.07.004.

[8] T. L. Chern, C. W. Chuang, and R. L. Jiang, "Design of discrete integral variable structure control systems and application to a brushless DC motor control," *Automatica*, vol. 32, no. 5, pp. 773–779, 1996, doi: 10.1016/0005-1098(95)00197-2.

[9] C. L. Chen, M. J. Jang, and K. C. Lin, "Modeling and high-precision control of a ball-screw-driven stage," *Precis. Eng.*, vol. 28, no. 4, pp. 483–495, 2004, doi: 10.1016/j.precisioneng.2004.03.001.

[10] D. P. Yu, G. S. Hong, and Y. S. Wong, "Profile error compensation in fast tool servo diamond turning of micro-structured surfaces," *Int. J. Mach. Tools Manuf.*, vol. 52, no. 1, pp. 13–23, 2012, doi: 10.1016/j.ijmachtools.2011.08.010.

[11] X. C. Xi, A. N. Poo, and G. S. Hong, "Improving contouring accuracy by tuning gains for a bi-axial CNC machine," *Int. J. Mach. Tools Manuf.*, vol. 49, no. 5, pp. 395–406, 2009, doi:

10.1016/j.ijmachtools.2008.12.005.

[12] Y. Setyoadi, R. Hermana, and F. D. Mulyanto, “Performance Analysis of The 3D Printer Corexy FDM Type With Area X=200 Y=200 Z=200 mm,” vol. 3, no. 1, pp. 26–33, 2022.

[13] A.-N. Poo, J. G. Boliinger, and G. W. YOUNKIN, “Dynamic Errors in Type 1 Contouring Systems,” vol. I, no. 4, pp. 477–484, 1972.

[14] S. S. Yeh and P. Lo Hsu, “Perfectly matched feedback control and its integrated design for multiaxis motion systems,” *J. Dyn. Syst. Meas. Control. Trans. ASME*, vol. 126, no. 3, pp. 547–557, 2004, doi: 10.1115/1.1789970.

[15] U. Mutilba, E. Gomez-Acedo, G. Kortaberria, A. Olarra, and J. A. Yagüe-Fabra, “Traceability of on-machine tool measurement: A review,” *Sensors (Switzerland)*, vol. 17, no. 7, pp. 1–37, 2017, doi: 10.3390/s17071605.

[16] circuitspecialists, “ESP32 Wifi & Bluetooth compatible microcontroller,” *circuitspecialists*, 2022. https://www.circuitspecialists.com/esp32.html (accessed Jul. 10, 2022).

[17] J. Qiu and R. Ge, “A theoretical model and experimental investigation to predict and evaluate cutting capability of turning center based on material removal rate,” *Int. J. Adv. Manuf. Technol.*, vol. 104, no. 9–12, pp. 3287–3302, 2019, doi: 10.1007/s00170-018-2006-x.

[18] F. Facchini, A. De Chirico, and G. Mummolo, “Comparative cost evaluation of material removal process and additive manufacturing in aerospace industry,” *Springer Proc. Math. Stat.*, vol. 280, pp. 47–59, 2019, doi: 10.1007/978-3-030-14969-7_5.

[19] ASME B 5.54:2005, *Methods for Performance Evaluation of Computer Numerically Controlled Machining Centers Methods for Performance Evaluation of Computer Numerically Controlled Machining Centers*, vol. 2005. 2015.

[20] A. Faizal, M. Sitepu, A. Faizal, J. T. Elektro, and F. Sains, “Analisis Sistem Kendali Hybrid Sliding Mode Control (SMC) -Fuzzy pada Inverted Pendulum,” vol. 14, no. 2, pp. 185–191, 2017.

[21] F. Betin and G. A. Capolino, “Sliding mode control for electrical drives,” *Proc. - 2015 IEEE Int. Electr. Mach. Drives Conf. IEMDC 2015*, no. May, pp. 1043–1048, 2016, doi: 10.1109/IEMDC.2015.7409190.