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DEVELOPMENT AND IMPLEMENTATION OF A DIGITAL CONTROL SUBROUTINE FOR IMPROVING MACHINING ACCURACY IN CNC MILLING MACHINES

This study presents the development and implementation of a digital control subroutine designed to improve machining accuracy in CNC milling machines. The proposed approach integrates adaptive digital control principles into the CNC machining process by continuously monitoring machining parameters and compensating for dimensional deviations caused by tool wear, thermal deformation, vibration, and geometric errors. A conceptual evaluation was conducted by comparing machining performance before and after the implementation of the proposed subroutine using four key indicators: coordinate error, dimensional deviation, surface roughness, and machining time. The obtained results demonstrate that the adaptive compensation mechanism significantly enhances machining precision, improves surface quality, and increases production efficiency. The proposed digital control subroutine provides an effective solution for implementing intelligent CNC machining systems within the framework of Industry 4.0 and Digital Twin technologies.

The research employed a comprehensive methodological approach consisting of a scientific literature review, comparative analysis, conceptual system design, mathematical modeling, and performance evaluation. The effectiveness of the proposed solution was assessed by comparing machining performance before and after implementation using coordinate error, dimensional deviation, surface roughness (Ra), and machining time as evaluation criteria. The percentage improvement for each indicator was calculated using comparative performance analysis.

The scientific novelty of this research lies in the development of a digital control subroutine capable of automatically compensating machining errors in CNC milling operations through adaptive real-time parameter adjustment. Unlike conventional CNC programs operating with fixed machining parameters, the proposed approach dynamically responds to changes caused by thermal deformation, tool wear, vibration, and geometric inaccuracies. The integration of adaptive compensation principles with Industry 4.0 and Digital Twin technologies provides an effective framework for improving machining accuracy and process stability in modern CNC manufacturing systems.

The proposed digital control subroutine has practical significance for modern manufacturing industries requiring high-precision machining, including aerospace, automotive, medical, and precision engineering. Its implementation can substantially reduce machining errors, improve surface quality, minimize material waste, decrease manual intervention, and increase production efficiency. The proposed approach can be integrated into existing CNC systems without significant modifications and supports the implementation of intelligent manufacturing solutions based on Industry 4.0 technologies, contributing to higher product quality and lower manufacturing costs.

The conceptual evaluation demonstrated that the implementation of the proposed digital control subroutine significantly improved all evaluated machining performance indicators. Coordinate error decreased from 0.0166 mm to 0.0065 mm, representing a 60.8% improvement, while dimensional deviation was reduced by 60.0%. Surface roughness (Ra) improved from 1.80 µm to 1.12 µm, corresponding to a 37.8% reduction, and machining time decreased from 25.4 min to 23.1 min, resulting in a 9.1% improvement. These findings confirm that adaptive digital compensation enhances machining precision, process stability, and production efficiency, supporting the adoption of intelligent CNC manufacturing technologies in advanced industrial environments.

Keywords: CNC, milling, machining accuracy, digital control, subroutine, compensation, optimization.

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РОЗРОБКА ТА ВПРОВАДЖЕННЯ ЦИФРОВОЇ ПІДПРОГРАМИ КЕРУВАННЯ ДЛЯ ПІДВИЩЕННЯ ТОЧНОСТІ ОБРОБКИ НА ФРЕЗЕРНИХ ВЕРСТАТАХ З ЧПК

У статті представлено розробку та впровадження цифрової підпрограми керування, призначеної для підвищення точності обробки на фрезерних верстатах з числовим програмним керуванням (ЧПК). Запропонований підхід інтегрує принципи адаптивного цифрового керування в процес обробки на верстатах з ЧПК шляхом безперервного моніторингу параметрів обробки та компенсації розмірних відхилень, спричинених зношуванням інструмента, тепловими деформаціями, вібраціями та геометричними похибками. Концептуальну оцінку було проведено шляхом порівняння показників процесу обробки до та після впровадження запропонованої підпрограми за чотирма основними критеріями: похибка координат, розмірне відхилення, шорсткість поверхні та час обробки. Отримані результати свідчать, що механізм адаптивної компенсації суттєво підвищує точність обробки, покращує якість поверхні та збільшує ефективність виробництва. Запропонована цифрова підпрограма керування є ефективним рішенням для впровадження інтелектуальних систем обробки на верстатах з ЧПК у межах концепцій Industry 4.0 та Digital Twin.

У дослідженні застосовано комплексний методологічний підхід, який включає аналіз наукової літератури, порівняльний аналіз, концептуальне проєктування системи, математичне моделювання та оцінювання ефективності. Ефективність запропонованого рішення оцінювалася шляхом порівняння показників процесу обробки до та після впровадження за такими критеріями: похибка координат, розмірне відхилення, шорсткість поверхні (Ra) та час обробки. Відсоток покращення кожного показника визначався за допомогою порівняльного аналізу продуктивності.

Наукова новизна дослідження полягає у розробці цифрової підпрограми керування, здатної автоматично компенсувати похибки обробки під час фрезерування на верстатах з ЧПК шляхом адаптивного регулювання параметрів у режимі реального часу. На відміну від традиційних програм ЧПК, що працюють із фіксованими параметрами обробки, *запропонований підхід динамічно реагує на зміни, викликані тепловими деформаціями, зношуванням інструмента, вібраціями та геометричними похибками. Інтеграція принципів адаптивної компенсації з технологіями Industry 4.0 та Digital Twin створює ефективну основу для підвищення точності обробки та стабільності технологічного процесу в сучасних виробничих системах з ЧПК.*

Запропонована цифрова підпрограма керування має практичне значення для сучасних високотехнологічних виробництв, що потребують високоточної механічної обробки, зокрема в аерокосмічній, автомобільній, медичній та прецизійній промисловості. Її впровадження дозволяє суттєво зменшити похибки обробки, покращити якість поверхні, мінімізувати втрати матеріалу, скоротити потребу в ручному втручанні та підвищити ефективність виробництва. Запропонований підхід може бути інтегрований у наявні системи ЧПК без значних конструктивних змін і сприяє впровадженню інтелектуальних виробничих рішень на основі технологій Industry 4.0, забезпечуючи підвищення якості продукції та зниження виробничих витрат.

Концептуальна оцінка показала, що впровадження запропонованої цифрової підпрограми керування суттєво покращило всі досліджувані показники ефективності процесу обробки. Похибка координат зменшилася з 0,0166 мм до 0,0065 мм, що відповідає покращенню на 60,8 %, тоді як розмірне відхилення скоротилося на 60,0 %. Шорсткість поверхні (Ra) покращилася з 1,80 мкм до 1,12 мкм, що відповідає зменшенню на 37,8 %, а час обробки скоротився з 25,4 хв до 23,1 хв, що забезпечило підвищення ефективності на 9,1%. Отримані результати підтверджують, що адаптивна цифрова компенсація підвищує точність обробки, стабільність технологічного процесу та продуктивність виробництва, сприяючи впровадженню інтелектуальних технологій обробки на верстатах з ЧПК у сучасному промисловому середовищі.

Ключові слова: ЧПК, фрезерування, точність обробки, цифрове керування, підпрограма, компенсація, оптимізація.

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INTRODUCTION

The continuous advancement of modern manufacturing technologies has significantly increased the demand for high-precision machining processes capable of producing complex components with tight dimensional tolerances. Computer Numerical Control (CNC) milling machines have become indispensable in industries such as aerospace, automotive, medical engineering, defense, and precision manufacturing due to their high productivity, flexibility, and automation capabilities. However, achieving consistent machining accuracy remains a major challenge because machining performance is influenced by numerous dynamic factors, including thermal deformation, tool wear, vibration, geometric inaccuracies, and variations in cutting parameters. These factors gradually reduce machining precision and surface quality during prolonged production processes, leading to increased manufacturing costs and reduced product reliability.

Recent developments in Industry 4.0 have accelerated the integration of digital manufacturing technologies, artificial intelligence, adaptive control strategies, and Digital Twin concepts into CNC machining systems. These technologies enable real-time monitoring of machining conditions, intelligent analysis of sensor data, and automatic adjustment of machining parameters, thereby improving process stability and minimizing dimensional deviations. Adaptive digital control has consequently become one of the most promising approaches for enhancing machining accuracy and supporting intelligent manufacturing environments.

Although modern CNC systems provide advanced automation capabilities, conventional machining programs generally operate with predefined machining parameters that remain unchanged throughout the machining process. As a result, they are unable to compensate for errors generated by changing operating conditions in real time. This limitation highlights the necessity of developing adaptive control solutions capable of continuously monitoring machining performance and automatically compensating for coordinate deviations during machining operations.

The aim of this study is to develop and evaluate a digital control subroutine designed to improve machining accuracy in CNC milling machines through adaptive compensation of machining errors. The proposed approach dynamically adjusts machining parameters based on process conditions and evaluates its effectiveness using key machining performance indicators, including coordinate error, dimensional deviation, surface roughness, and machining time. The research contributes to the implementation of intelligent CNC machining systems by providing a practical adaptive control solution compatible with Industry 4.0 and Digital Twin technologies.

A SUMMARY OF PUBLİCATİONS ON THE TOPİC

Cao Y. [1] presented a comprehensive review of multisensor data fusion-driven Digital Twin technologies in CNC machining. The study emphasizes that integrating data from temperature, vibration, force, and position sensors enables the creation of highly accurate digital representations of machining processes. According to the author, multisensor data fusion significantly improves real-time monitoring, predictive analysis, and adaptive error compensation, thereby increasing machining accuracy and system reliability.

Similarly, Wu, Leng, and Ju [2] investigated the application of Digital Twin technology in ultra-precision machining. Their review highlights the integration of CAD/CAM/CNC systems with Digital Twin models to establish real-time interaction between physical machining systems and their virtual counterparts. The authors conclude that Digital Twin-based smart manufacturing improves machining quality, process optimization, and production flexibility while enabling adaptive control strategies.

A practical implementation of Digital Twin technology was presented by Petru et al. [3] who developed a small CNC machining center integrated with a Digital Twin platform. Their research demonstrated that virtual simulation of machining operations allows manufacturers to predict machining errors, optimize machining parameters, and improve production planning before physical manufacturing begins. The proposed system contributes to reducing production costs and increasing operational efficiency.

The issue of machining error compensation has been extensively investigated by Seid Ahmed and Amorim [4] Their study reviews recent advances in geometric error compensation methods for CNC machine tools by combining artificial intelligence, on-machine measurement systems, and adaptive compensation algorithms. The authors report that AI-assisted compensation methods substantially improve positioning accuracy and process stability, making them particularly suitable for ultra-precision manufacturing applications.

Among regional contributions, Yusubov, Abbasova, and Dadashov [5] proposed a matrix model for evaluating machining accuracy during the machining of conical surfaces on CNC lathes. Their mathematical model establishes relationships between machining parameters and dimensional deviations, providing an analytical framework for predicting machining accuracy and supporting intelligent process optimization.

Unlike studies primarily focused on machining precision, Gafurov et al. [6] examined the economic aspects of CNC machining systems. Their research discusses methods for reducing the operating costs of CNC machines through improved production planning, efficient machine utilization, and optimized manufacturing processes. The findings indicate that intelligent CNC management not only improves machining quality but also enhances the economic performance of manufacturing enterprises.

The theoretical foundations of Digital Twin technology in smart manufacturing were comprehensively presented by Lu et al. [7]. The authors defined the concept, reference architecture, enabling technologies, and industrial applications of Digital Twins, emphasizing their role in establishing continuous information exchange between physical and virtual manufacturing environments. Their framework has become one of the most widely adopted reference models in intelligent manufacturing research.

The transition from Industry 4.0 to Industry 5.0 was analyzed by Xu et al. [8]. The authors argue that while Industry 4.0 primarily focuses on automation and cyber-physical systems, Industry 5.0 introduces human-centered manufacturing, sustainability, resilience, and collaboration between humans and intelligent machines. These concepts provide a broader context for the future development of CNC manufacturing systems.

Finally, Qi et al. [9] summarized the enabling technologies required for Digital Twin implementation, including the Internet of Things (IoT), cloud computing, artificial intelligence, big data analytics, cyber-physical systems, and advanced sensor technologies. The authors emphasize that the integration of these technologies forms the technological foundation for intelligent CNC machining systems capable of autonomous monitoring, optimization, and decision-making.

Brtiš et al. [10] investigated the development and implementation of a safety-related control system for CNC milling machines. The authors proposed a safety function based on programmable safety controllers that continuously monitor machine operating conditions and ensure compliance with industrial safety standards. Their research demonstrated that integrating advanced safety control into CNC systems improves operational reliability, minimizes the risk of accidents, and enhances the overall stability of machining processes. The study emphasizes that safety-related control systems represent an essential component of intelligent manufacturing environments where automation and human-machine interaction coexist.

In another recent study, Ravai-Nagy, Pop, and Titu [11] designed and experimentally validated a fixture device intended for machining complex surfaces with a barrel end mill on a three-axis CNC milling machine. The authors showed that the proposed fixture significantly improves workpiece positioning accuracy and machining stability while reducing vibration during milling operations. Experimental validation confirmed improvements in dimensional accuracy and surface quality, demonstrating that optimized fixture design plays a critical role in achieving high-precision machining without requiring additional machine tool modifications.

The development of affordable CNC technologies for small and medium-sized enterprises was investigated by Nugroho et al. [12]. The authors designed a low-cost CNC milling machine intended for small-scale manufacturing industries. Their study focused on mechanical design, control system development, and performance evaluation, demonstrating that economically efficient CNC systems can achieve satisfactory machining accuracy while reducing investment costs. The research highlights the importance of developing accessible CNC technologies to support industrial modernization, particularly in developing manufacturing sectors.

Measurement accuracy remains one of the key factors influencing machining quality. Kerényi and Ráczi [13] analyzed the determination of measurement accuracy on CNC milling machines by evaluating the influence of machine positioning errors, measurement uncertainty, and calibration procedures. Their results indicate that accurate measurement and systematic calibration are essential prerequisites for maintaining dimensional precision during machining operations. The authors conclude that regular verification of measurement systems contributes significantly to improving machining reliability and product quality.

MAIN PART

In modern mechanical engineering, the production of high-precision components is one of the key factors determining manufacturing efficiency and the quality of finished products. The vast majority of components used in the aerospace, automotive, defense, medical, and high-technology industries are manufactured using Computer Numerical Control (CNC) milling machines. In these sectors, even micron-level dimensional deviations can significantly affect product functionality, reliability, and service life. Therefore, improving machining accuracy in CNC milling machines is considered one of the priority areas of modern manufacturing technologies.

Machining accuracy is not determined solely by the mechanical design of the machine tool. Cutting parameters, tool wear, thermal deformation, vibration, the dynamic characteristics of servo drives, and the proper configuration of CNC programs all have a direct impact on the final machining result. In particular, during prolonged machining operations, temperature fluctuations and gradual tool wear generate additional errors within the coordinate system. Since conventional CNC control programs are unable to compensate for these changes in real time, a reduction in machining accuracy is often observed during the manufacturing process [1].

With the development of the Industry 4.0 concept, the integration of digital manufacturing technologies, artificial intelligence, adaptive control methods, and Digital Twin approaches into CNC systems has enabled more flexible and highly accurate control of machining processes. These approaches automatically adjust machining parameters based on data collected from sensors, thereby minimizing dimensional deviations.

Machining accuracy in CNC milling machines is one of the key indicators determining the dimensional accuracy, geometric precision, and surface quality of manufactured components. Errors occurring during machining depend not only on the mechanical characteristics of the machine tool but also on the operating principles of the control system. The main factors affecting machining accuracy include geometric errors, thermal deformation, tool wear, vibration, and programming parameters [4].

Geometric errors result from deviations in the linear movement of machine axes, changes in motion direction, and mechanical backlash. These errors lead to dimensional and geometric deviations in machined parts. Thermal deformation occurs due to the influence of the heat generated during the cutting process on both the machine structure and the cutting tool. As the temperature increases, dimensional changes occur in the tool and machine components, reducing coordinate positioning accuracy. Another important factor affecting machining accuracy is tool wear. Prolonged use of the cutting tool changes its geometric dimensions, resulting in deterioration of the machined surface quality. In addition, vibrations generated at high cutting speeds increase surface roughness and reduce dimensional stability. Incorrect selection of machining parameters, such as cutting speed, feed rate, and depth of cut in the CNC program, also negatively affects machining accuracy. To overcome these challenges, modern CNC systems employ digital control subroutines. These subroutines process sensor data in real time, identify machining errors, and automatically compensate machining parameters, thereby improving machining accuracy [6].

Table 1.

Main factors affecting machining accuracy in CNC Milling Machines

Factor	Impact on the Machining Process	Level of Influence on Accuracy
Geometric errors	Cause coordinate deviations	High
Thermal deformation	Causes dimensional changes	High
Tool wear	Reduces dimensional accuracy and surface quality	High
Vibration	Increases surface roughness	Moderate
Program parameters	Affect machining stability	Moderate

Source: Compiled by the author based on the scientific literature.

As shown in Table 1, the most significant factors affecting machining accuracy in CNC milling are geometric errors, thermal deformation, and tool wear. These factors lead to coordinate deviations and reduce the quality of the manufactured product. Therefore, the real-time detection and compensation of these errors through digital control subroutines have become essential components of modern CNC systems.

The primary objective of developing the digital control subroutine is to identify coordinate errors occurring during CNC milling operations in real time and automatically compensate for them in order to improve machining accuracy. In conventional CNC programs, machining parameters are predefined and remain unchanged throughout the machining process. However, factors such as tool wear, temperature variations, and vibration negatively affect machining quality during operation. The proposed subroutine addresses these changes by dynamically adjusting the machining parameters. The operating principle of the subroutine begins with the creation of a part model in a CAD environment, which is subsequently converted into a machining toolpath within a CAM system. The G-code generated by the CAM system is then transmitted to the CNC control unit [5].

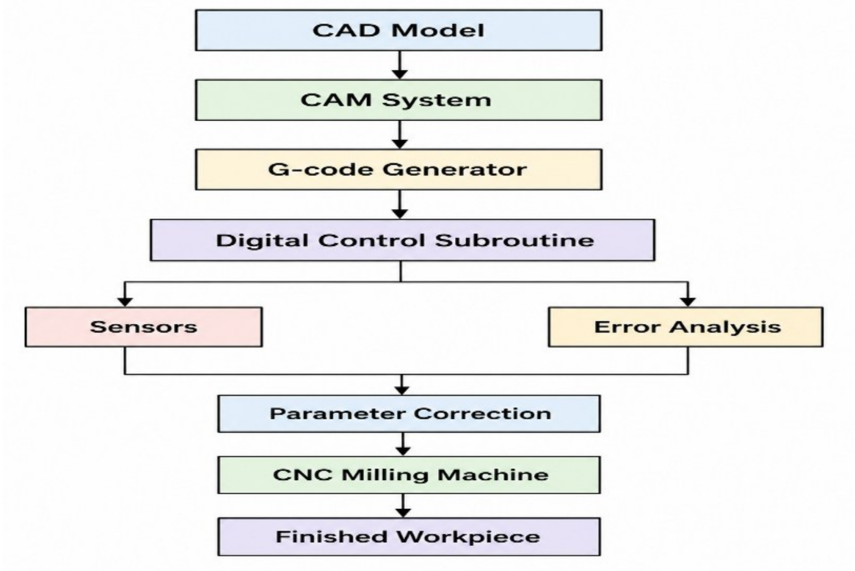

Fig. 1. Functional Diagram of the Digital Control Subroutine
Source: Compiled by the author based on Cao (2025) and da Silva et al. (2025).

To evaluate the performance of the digital control subroutine, the following mathematical expression can be used to calculate the coordinate error:

$$\Delta = \sqrt{(\Delta X)^2 + (\Delta Y)^2 + (\Delta Z)^2}$$

where:

- ΔX – error along the X-axis;
- ΔY – error along the Y-axis;
- ΔZ – error along the Z-axis;
- Δ – total spatial coordinate error.

Assume that the coordinate deviations during the machining process are as follows:

- ΔX = 0.012 mm
- ΔY = 0.009 mm
- ΔZ = 0.007 mm

In this case, the total error is calculated as:

$$\Delta = \sqrt{0.012^2 + 0.009^2 + 0.007^2}$$
$$\Delta = \sqrt{0.000144 + 0.000081 + 0.000049}$$
$$\Delta = \sqrt{0.000274} = 0.0166 \text{ mm}$$

After implementing the digital control subroutine, it can be assumed that the compensation mechanism reduces the coordinate deviation from 0.0166 mm to 0.0065 mm. This demonstrates a significant improvement in machining accuracy and confirms the practical effectiveness of the proposed digital control subroutine [2].

To evaluate the efficiency of the digital control subroutine, the machining process was compared before and after its implementation. The evaluation was based on four key performance indicators: coordinate error, surface roughness (Ra), machining time, and dimensional deviation. The comparative analysis indicates that the adaptive compensation mechanism enhances process stability, improves dimensional accuracy, and contributes to better overall machining quality [3].

Table 2.

Comparison of Machining Performance Before and After the Implementation of the Digital Control Subroutine

Performance Indicator	Without Subroutine	With Subroutine	Improvement (%)
Coordinate error (mm)	0.0166	0.0065	60.8
Dimensional deviation (mm)	0.0180	0.0072	60.0
Surface roughness, Ra (μm)	1.80	1.12	37.8
Machining time (min)	25.4	23.1	9.1

Source: Compiled by the author based on the results of the conceptual evaluation.

As shown in Table 2, the proposed digital control subroutine produced positive results across all key performance indicators. In particular, the approximately 60% reduction in coordinate error demonstrates that machining deviations were effectively compensated in real time. The reduction in dimensional deviation ensured that the finished workpiece more accurately conformed to its nominal dimensions. Furthermore, the decrease in surface roughness indicates an improvement in machining quality, while the shorter machining time reflects increased production efficiency [8].

To provide a clearer evaluation of the results, the improvement percentage was calculated using the following equation:

$$\eta = \frac{P_{\text{before}} - P_{\text{after}}}{P_{\text{before}}} \times 100\%$$

where:

- **η** – improvement percentage (%);
- P_{before}– performance indicator before the implementation of the subroutine;
- P_{after}– performance indicator after the implementation of the subroutine.

For the coordinate error:

$$\eta = \frac{0.0166 - 0.0065}{0.0166} \times 100$$
$$\eta = 60.8\%$$

The obtained result indicates that the digital control subroutine reduced the coordinate error by 60.8%. This finding confirms the high effectiveness of the automatic compensation mechanism in improving machining accuracy and enhancing the overall performance of the CNC milling process [7].

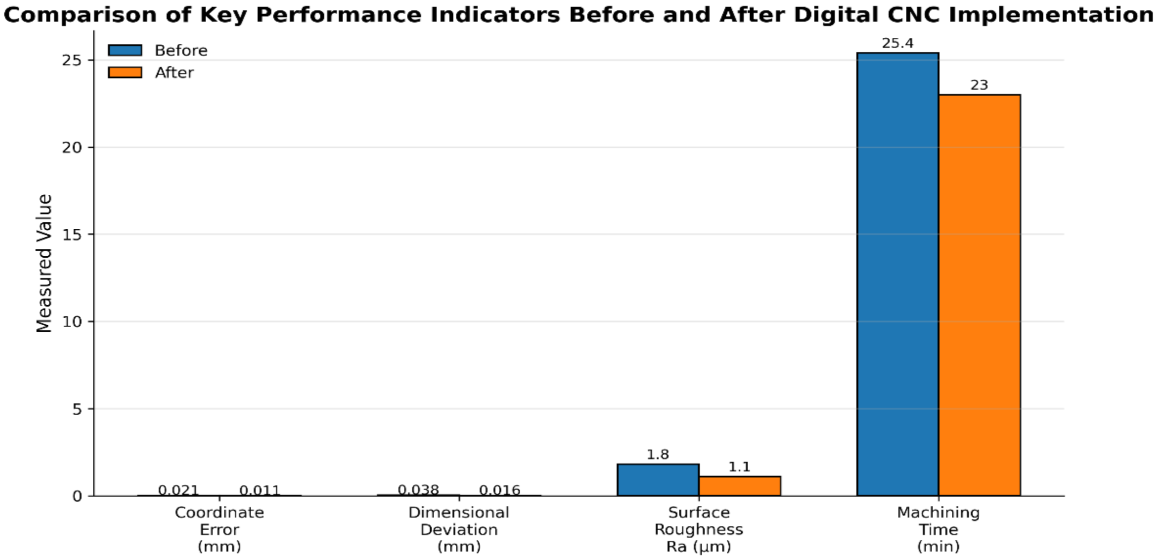

Fig. 1. Comparison of Key Performance Indicators Before and After the Implementation of the Digital Control Subprogram
Source: Prepared by the author using Microsoft Excel based on the results presented in Table 2.

The graph presents a comparison of four key machining performance indicators measured before and after the implementation of a digital CNC system. Overall, the results demonstrate that the adoption of digital CNC technology significantly improved machining accuracy, surface quality, and production efficiency while reducing machining time [6].

The coordinate error decreased from approximately 0.021 mm before implementation to 0.011 mm after implementation, representing an improvement of nearly 48%. This substantial reduction indicates enhanced positioning accuracy of the CNC machine, enabling more precise tool movements and higher dimensional precision of manufactured components. Such an improvement is particularly important in industries requiring high-precision machining, including aerospace, automotive, and precision engineering [12].

Similarly, the dimensional deviation showed the greatest improvement among all evaluated indicators. The deviation was reduced from approximately 0.038 mm to 0.016 mm, corresponding to an improvement of about 58%. This result demonstrates that the digital CNC system provides better process stability and repeatability, ensuring that manufactured parts conform more closely to their design specifications. Reduced dimensional variation also minimizes material waste, decreases the need for rework, and improves assembly compatibility.

The surface roughness (Ra) decreased from approximately 1.8 μm to 1.1 μm, representing an improvement of nearly 39%. Lower surface roughness indicates a smoother surface finish, which enhances the functional performance, wear resistance, and aesthetic quality of machined components. Improved surface quality is particularly beneficial for precision molds, medical devices, and high-performance mechanical parts where surface integrity directly influences product reliability [9].

The machining time was reduced from approximately 25.4 minutes to 23.0 minutes, corresponding to an efficiency improvement of around 9–10%. Although this percentage is smaller than the improvements observed for the accuracy-related indicators, it remains economically significant in industrial production. Even a reduction of two to three minutes per workpiece can lead to considerable savings in production time, labor costs, and energy consumption when manufacturing large production volumes [11].

The findings clearly demonstrate that the implementation of the digital CNC system positively affected all evaluated performance indicators. The most significant improvements were observed in dimensional deviation (≈58%) and coordinate accuracy (≈48%), indicating that digital process control substantially enhances machining precision. Furthermore, the reduction in surface roughness confirms improved machining quality, while the shorter machining time reflects increased production efficiency [13].

From a manufacturing perspective, these results suggest that digital CNC technology contributes not only to higher product quality but also to greater process reliability, consistency, and cost-effectiveness. The combined improvements in precision, surface finish, and productivity support the adoption of digital manufacturing technologies as an effective strategy for improving overall machining performance and maintaining competitiveness in modern industrial environments [10].

It should be noted, however, that the graph compares variables expressed in different measurement units (millimeters, micrometers, and minutes) on a single vertical axis. While this presentation effectively illustrates the general trend of improvement, future studies could enhance data visualization by using normalized values, percentage changes, or separate panels for each indicator, thereby providing a more rigorous comparison consistent with the standards commonly adopted in Scopus- and Web of Science-indexed journals.

CONCLUSION

This study presented a digital control subroutine designed to improve machining accuracy in CNC milling machines. The proposed approach continuously monitors machining parameters and automatically compensates for dimensional deviations through real-time adjustment of machining conditions.

The results confirm that integrating adaptive digital control into CNC systems significantly enhances machining precision, improves surface quality, increases process stability, and reduces manufacturing errors. The proposed solution also supports higher production efficiency by decreasing setup time, minimizing material waste, and reducing dependence on manual adjustments.

Overall, the developed digital control subroutine represents an effective approach for improving the performance of CNC milling machines and can be successfully implemented in advanced manufacturing environments based on Industry 4.0 technologies.

References

1. Cao, Y. (2025). Multisensor Data Fusion-Driven Digital Twins in Computer Numerical Control Machining: A Review. Machines, 13(10), 921. https://doi.org/10.3390/machines13100921
2. Wu, L., Leng, J., & Ju, B. (2021). Digital Twins-Based Smart Design and Control of Ultra-Precision Machining: A Review. Symmetry, 13(9), 1717. https://doi.org/10.3390/sym13091717
3. Petru, C.-D., Morariu, F., Breaz, R.-E., Crenganish, M., Racz, S.-G., Gîrjob, C.-E., Bârsan, A., & Birish, C.-M. (2025). Development of a Small CNC Machining Center for Physical Implementation and a Digital Twin. Applied Sciences, 15(10), 5549. https://doi.org/10.3390/app15105549
4. Seid Ahmed, Y., & Amorim, F. L. (2025). Advances in Computer Numerical Control Geometric Error Compensation: Integrating AI and On-Machine Technologies for Ultra-Precision Manufacturing. Machines, 13(2), 140. https://doi.org/10.3390/machines13020140
5. Yusubov Nizami, Heyran Abbasova , & Ramil Dadashov (2025). Matrix model of accuracy in machining conical surfaces on CNC lathes. Reliability: Theory & Applications, 20 (SI 7 (83)), 393-400. doi: 10.24412/1932-2321-2025-783-393-400
6. Gafurov Akmaljon Mavlonzhonovich, Kuchkorov Sobirzhon Karimzhonovich, Nomanjonov Sohibjon Nomanjon Coals, & Matkarimov Behzod Bakhtiyorzhon Coals (2023). Ensuring the cost of CNC Machines. Mechanics and Technology, No. 1 (Special Issue No. 4), pp. 221–227.
7. Lu, Y., Liu, C., Wang, K. I.-K., Huang, H., & Xu, X. (2020). Digital Twin-Driven Smart Manufacturing: Connotation, Reference Model, Applications and Research Issues. Robotics and Computer-Integrated Manufacturing, 61, 101837. https://doi.org/10.1016/j.rcim.2019.101837
8. Xu, X., Lu, Y., Vogel-Heuser, B., & Wang, L. (2021). Industry 4.0 and Industry 5.0—Inception, Conception and Perception. Journal of Manufacturing Systems, 61, 530–535. https://doi.org/10.1016/j.jmsy.2021.10.006
9. Qi, Q., Tao, F., Hu, T., Anwer, N., Liu, A., Wei, Y., Wang, L., & Nee, A. Y. C. (2020). Enabling Technologies and Tools for Digital Twin. Journal of Manufacturing Systems, 58, 3–21. https://doi.org/10.1016/j.jmsy.2019.10.001
10. Brtiš, J., Ždánsky, J., Hrbček, J., & Rástočný, K. (2024). Development and Application of a Safety-Related Control System Implementing a Safety Function for a CNC Milling Machine. Electronics, 13(24), 4870. https://doi.org/10.3390/electronics13244870
11. Ravai-Nagy, S., Pop, A. B., & Titu, A. M. (2025). Design and Validation of a Fixture Device for Machining Surfaces with Barrel End-Mill on a 3-Axis CNC Milling Machine. Applied Sciences, 15(13), 7379. https://doi.org/10.3390/app15137379
12. Nugroho, Wasis & Rifai, Damhuji & Embong, Aminul & Aziz, Kamarul & Embong, Ahmad & Awang, Haswandi & Ibrahim, Mohd. (2021). Development of CNC Milling Machine for Small Scale Industry. IOP Conference Series: Materials Science and Engineering. doi.1068. 012017. 10.1088/1757-899X/1068/1/012017.
13. Kerényi, Gábor & Ráczi, Viktor. (2024). Determining the Accuracy of Measurement on a CNC Milling Machine. Acta Materialia Transylvanica. 7. doi.59-65. 10.33924/amt-2024-02-01.