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Two-sided manual machining method for three-axis CNC milling machine for small and medium-sized enterprises

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Abstract

Small and medium-sized enterprises (SMEs) have a big role in Indonesian economic development. The government has set four strategies in an effort to boost Indonesian economic development. One of the four strategies mentions the SMEs, and the other mentions the use of 4.0 technology. Working capital has been the main issue need to be considered in the SMEs. Thus, the affordability must be considered in the use of 4.0 technology in SMEs. One of the 4.0 technologies that are possible to be used in the SMEs is a three-axis milling machine. One of the limitations of the machine is that it cannot do the back-side machining process. The paper examines the possibility of manual back-side machining on the three-axis milling machine without adding a rotary axis. Four methods were conducted by adding two-point markings on the *x*-axis, two-point markings on the *y*-axis, four-point markings on the *x*- and *y*-axis, and four-point markings on the *x*- and *y*-axis plus a series of offsetting processes. After conducting several qualitative observations and measurements on the mismatched position of the front and the back machining, and also analyzing the problems that emerged during the processes of the four different methods, it is concluded that adding four points markings on the *x*- and *y*-axis plus doing a series of offsetting processes is the best method to have two-sided manual machining with three-axis computer numerical control (CNC) milling machine.

Keywords: computer numerical control (CNC); small and medium-sized enterprises (SMEs); three-axis; two-sided machining.

I. Introduction

The Indonesian government establishes four strategies to boost economic development. Two of the four strategies mention small and medium-sized enterprises (SMEs) and the use of 4.0 technology. The main problem that emerged in SMEs is working capital. It must be admitted that the SMEs still have to deal with technical skills and capital resources, but they recognize the benefit of 4.0 Technology for their production line [1]. In terms of adopting 4.0 technology, research suggests that SMEs are concerned about how the investment should be compared with the benefit [2].

One of the 4.0 technology that is possible to be used in SMEs is a three-axis milling machine [3]. Three-axis milling machine is considered to be a 4.0 technology for its advantage in terms of automation, which enables users to have the machine make a prototype based on a digital design created by the user. The advantages provide possibilities to do repeated production in a controlled standard [4]. There is research on building affordable three-axis milling machine that emphasizes the production cost [5][6], easy assembly method [7][8], low-cost computer numerical control (CNC) with specific function [9][10], portability [11], and size [12]. There is also some research about the use of three-axis milling machines for SMEs [13][14][15]. One of the limitations of the machine is that it cannot do a back-side machining process. The purpose can usually be done with the four-axis milling machine.

Previous researches try to modify the three-axis milling machine into four-axis [16] and five-axis by adding another axis [17]. Adding a rotary axis to a three-axis milling machine has been proven to

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produce complex products such as gears [16]. A rotary axis needs to be added in the effort, meaning the need for a bigger working table and more investment is required, while the miniaturization of the machine emerged in recent years aims to reduce investment in machines and production costs [18]. A smaller four-axis CNC machine that is able to perform back-side machining is already developed by E. E. Wai and S. S. Aung [19], but still, the design needs to add a rotary axis. This paper examines the possibility of doing back-side machining on the three-axis milling machine instead of adding a rotary axis and modifying it into a four-axis milling machine.

II. Materials and Methods

The basic principle for doing the two-sided machining process in a four-axis milling machine is to keep the *x*-, *y*-, and *z*-axis on the back-side process at the same position as it is on the front side. The paper will only focus on keeping the *x*- and *y*-axis in the proper place. The *z*-axis setting will be performed using the common method used in a three-axis milling machine that does not use a sensor to determine the (0,0,0) point position of the *x*-, *y*-, *z*-axis. This paper offers four methods for the purpose.

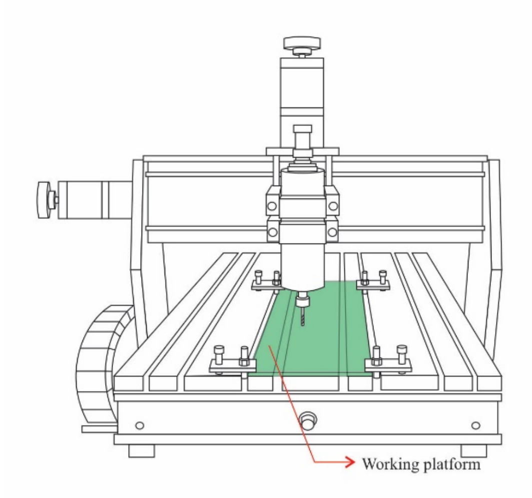


Figure 1. Working platform setting

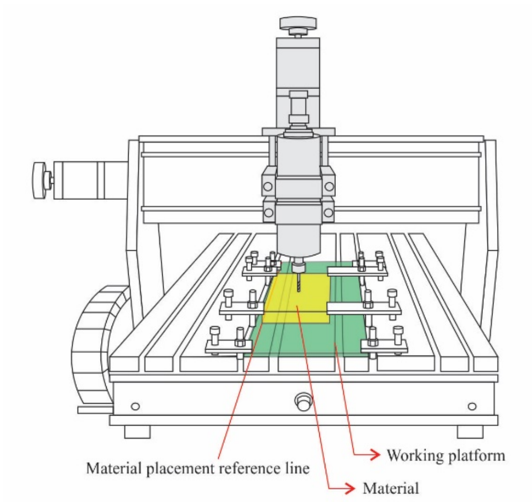


Figure 2. Material setting

The experiment is done with the China CNC zone three-axis milling machine. The Software used for the research is Mach 3 ver. 2.0 and ArtCam Jewelsmith ver 8.1. A piece of 3 mm plywood is then set as a working platform on the working table (Figure 1) to allow the process to make marks on the platform. The material used for the experiments is 15 mm Pine Wood (softwood), measured 90 mm wide with the length varies from 100 to 170 mm. The material was then fastened on the working platform (Figure 2).

There are two basic machining stages prepared for the experiment: roughing (raster in closed vector) and offset along the curve. The tool used is Hard Endmill, 3.175 in diameter, 2 flutes, and 20 mm flute length. The tool federate is 3 mm/s, with 40% step over, and 1 mm step down. The $z = 0$ is set on top of the material. Each process can be done multiple times for different purposes and other settings will be added for certain specific purposes that need to be done to make each of the four methods give the best results.

The four manual two-sided machining methods examined are:

- Method 1: Two-point markings on x-axis
- Method 2: Two-point markings on y-axis
- Method 3: Four-point markings on x-axis plus two-point markings on y-axis
- Method 4: Four-point markings x-axis and y-axis with offset checking

A. Method 1: Two-point markings on x-axis

Two-point marking is made on a working platform set on top of the working table. The marking is made on each tip of the material side on the *x*-axis (with *y*-axis = 0) (Figure 3) and the machine path on making marking is shown in Figure 4. The markings will keep the *x*-axis in the same position on the front-side as on back-side machining, and the imaginary lines created by the two marking points will also act as the feature that can keep the *y*-axis in place.

The processes made on each side are described as follows:

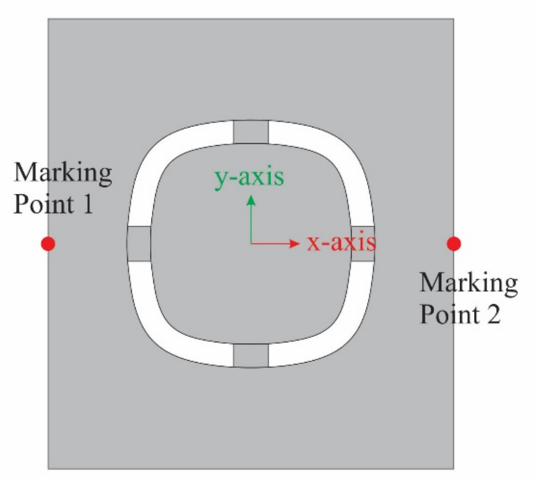


Figure 3. Two markings on *x*-axis

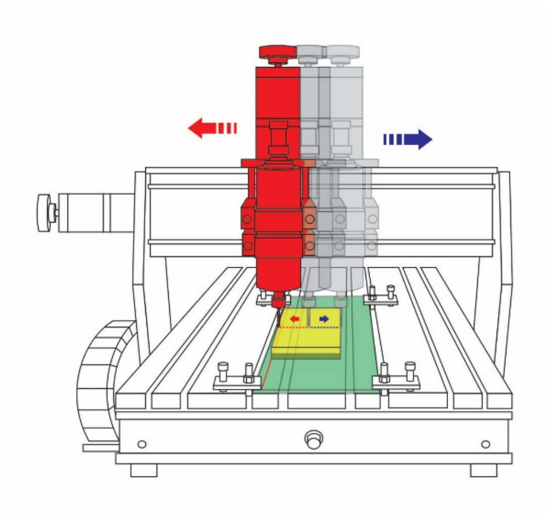


Figure 4. Machine path on making markings

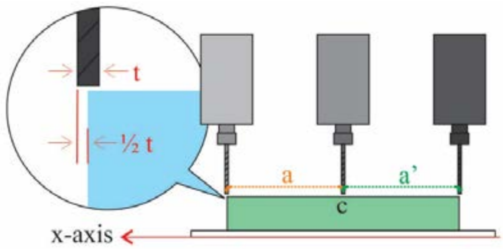


Figure 5. Guidance on making the two markings on x-Axis

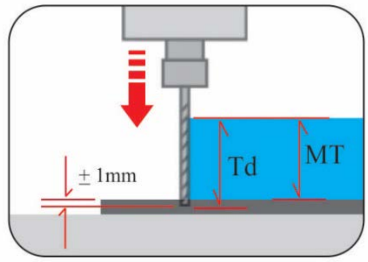
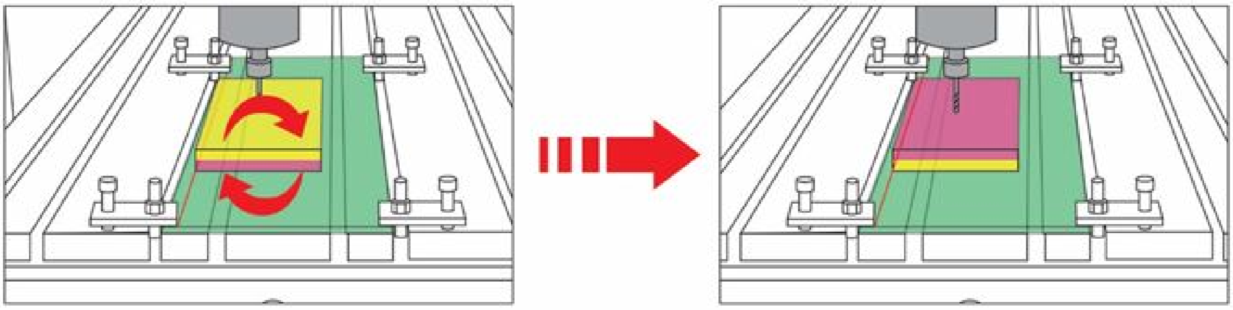


Figure 6. Tool depth in making the markings



Front side Back side

Figure 7. Flipping material to do back-side machining

1) Method 1 - front side

The roughing process is applied to slowly carve the material block into the rough desired shapes. The offset 1 process is applied in order to reach the precise outline of the desired shapes. The offset 2 process is applied to ensure that the shape remains exactly as desired.

The x-axis marking process is applied to make two markings on each side of the material and the working platform as references when flipping the material to do the back-side machining (Figure 5).

$$a' = -a$$
$$a = \pm\frac{1}{2}\text{material width} \quad (1)$$

where t is tool diameter, c is center zero ($(x, y, z) = (0,0,0)$), a is distance from center zero to marking point 1 (on the x-axis), and a' is distance from center zero to marking point 2 (on the x-axis).

The tool depth in making the markings is approximately the measurement of the material thickness plus 1 mm (Figure 6).

$$Td = MT + 1\text{ mm} \quad (2)$$

where Td is tool depth/tool final pass and MT is material thickness.

2) Method 1 - back side

The material flipped with the y-axis is considered to be the rotary axis (shown in Figure 7). The roughing process is applied to slowly carve the material block into the rough desired shapes. The offset 1 process is applied in order to reach the precise outline of the desired shapes. The result will be compared to the same process done on the front side. The offset 2 process is applied to remove the holder of the main shape.

B. Method 2: Two-point markings on y-axis

In this method, two-point marking is made on a working platform, on each tip of the material side on the y-axis (with x-axis = 0) (Figure 8), by moving the spindle along the y-axis (Figure 9).

The distance between the $y = 0$ points to the marking point at the top and bottom of the material does not have to be the same since the material is going to be rotated on the y-axis. The imaginary lines created by the two marking points will also act as the feature that can keep the x-axis in place. The processes made on each side are almost the same as the processes on the first method (two-point markings on the x-axis), except for the markings step:

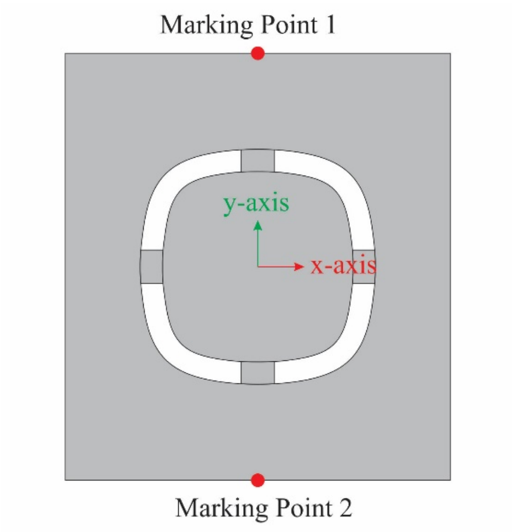


Figure 8. Two markings on *y*-axis

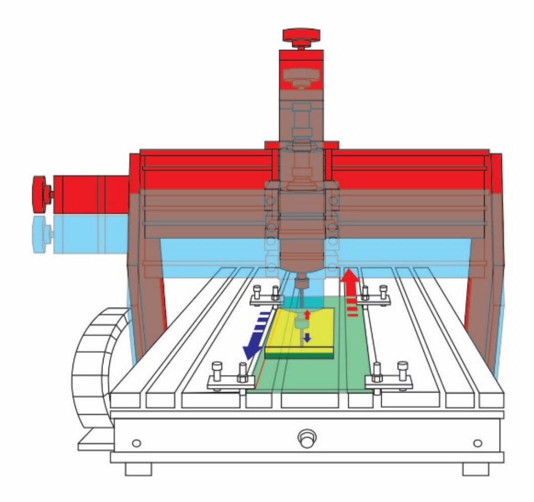


Figure 9. Machine path on making markings

1) Method 2 - front side

Roughing, offset 1, offset 2, and the y-axis marking process will be performed on the front side. The *y*-axis marking is applied to make two markings on each top and bottom side of the material and the working platform (on the *y*-axis/$y = 0$) (Figure 10) as the references when flipping the material to do the back-side machining process.

The distance of "a" or "a′" in Figure 5 is not necessarily the same as the distance of "b" or "b′"

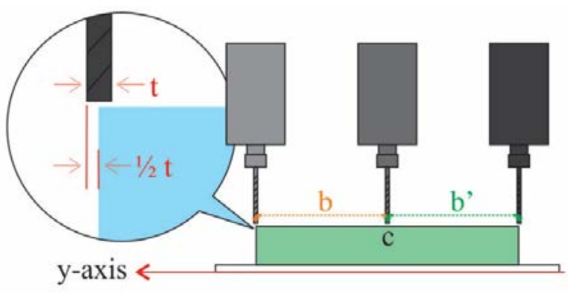


Figure 10. Guidance on making the two markings on *y*-axis

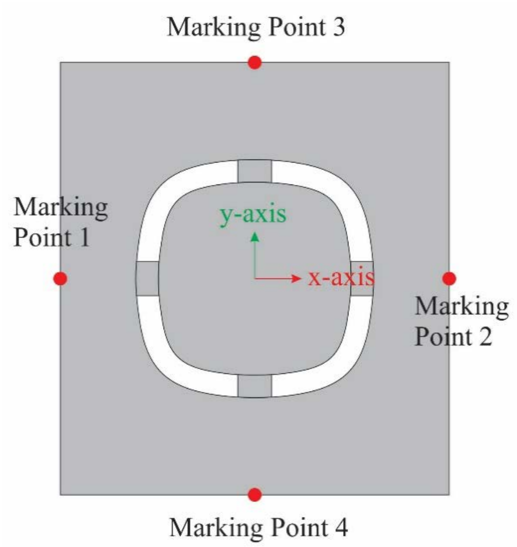


Figure 11. Four markings on *x*-axis and *y*-axis

in Figure 10, as it depends on the size of the products and the materials provided. In method 1, the distance of "a" must be the same as the distance of "a′", since the two markings are not positioned on the flipping axis (Figure 5). The distance of "b" does not have to be the same as "b′" since the flipping axis and the two markings are on the same axis (*y*-axis) (Figure 10).

$$b' \neq b \quad (3)$$

where t is tool diameter, c is center zero ($(x, y, z) = (0,0,0)$), b is distance from center zero to marking point 1 (on *y*-axis), and b' is distance from center zero to marking point 2 (on *y*-axis).

2) Method 2 - back side

The procedures conducted in the back side of Method 2 is similar as the procedure conducted in Method 1.

C. Method 3: Four-point markings on x-axis plus two-point markings on y-axis

In this method, four-point marking is made on a working platform set on top of the working table. The two markings are made on each tip of the material side on the *x*-axis (with *y*-axis = 0), and the other two markings are made on each tip of the material side on the *y*-axis (with *x*-axis = 0) (Figure 11). The distance between the $x = 0$ point and the marking point at the right and left sides of the material is the same, while the distance between the $y = 0$ point and the marking point at the top and the bottom of the material does not have to be the same. The two points on the *x*-axis and the other two on the *y*-axis will compensate for each other and keep the *x*- and *y*-axis at the same place, both on the front and the back side of the material machining processes.

The processes on each side are almost the same as the processes on the method 1 (two-point markings on *x*-axis), except for the markings step. The method combines the markings on the *x*-axis and *y*-axis:

1) Method 3 - front side

The procedures conducted in the front side of Method 3 is similar as the procedure conducted in Method 1 and Method 2, except for adding both *x*- and *y*-axis marking.

2) Method 3 - back side

The procedures conducted in the back side of Method 3 is similar as the procedure conducted in Method 1 and Method 2.

D. Method 4: Four-point markings x-axis and y-axis with offset checking

Many factors can affect the accuracy of the machining process. The hardness of the material, the tool strength [20], the tool design, and any other potential cutting parameters [21] can affect the accuracy of the machining results. There is a possibility that the tool might bend during the marking-point making or be deformed because of the heat generated when the tool penetrates through some hard materials like hardwoods, acrylic, resin, or steel [22].

Tool deflection has become one of the major causes of volumetric errors of produced parts [23]. Thus, the marking point position at the first contact between the tool and the material might not be the same as at the bottom of the material. This will generate difficulties in adjusting the marking position on the back-side machining processes.

Another series of offsetting processes were added to the previous method to ensure the precision of the back-side machining process. Two rectangular shapes were added at the top and bottom sides of the main product (Figure 12). The rectangular shapes have then been offset at both the front and back sides machining processes (Figure 13). If, after the back-side offset process, it is found that there is a gap as a result of the mismatched *x*- and *y*-axis position, manual adjustment can be made to match the *x*- and *y*-axis position.

1) Method 4 - front side

Roughing is done from the top to the bottom of the material. The top and bottom rectangular shape roughing process is performed to make a hole on the top and bottom of the main object's rastered area. It is made to ensure that the top and bottom holes are created in specific measurements. The main object offset is applied in order to reach the precise outline of the desired shapes. The *x*- and *y*-axis marking processes are applied to make two marking points on each side of the material, the working platform (*x*-axis markings), each outer side of the rectangular holes, and the working platform (*y*-axis markings), similar to method 3.

2) Method 4 - back side

The first consideration in doing back-side machining is that the *x*- and *y*-axis have to be already at the same position as it is in the front-side machining. A series of offset checking is performed as additions after setting the marking on the material in its proper place (at the reference/marking points made on the working platform). The back-side machining started with an offset process along the top and bottom rectangular shape. If the offset markings seem mismatched, the zero position ($(x, y) = (0,0)$) can be adjusted by manually moving the position to the *x*- or *y*-axis in the machining software (Mach 3 Ver 2.0) to the position considered to be the correct new zero *x*- or *y*-axis position. After the position seems correct, the offset process for the main object can be done. If the offset process leaves a mark on the main object indicating a mismatching position, the zero position ($(x, y) = (0,0)$) can be readjusted. The process can be done until the offset no longer leaves a mismatched mark on the main object. The Roughing process follows the process above. The offset process can be done to see if the position of the main object of the back-side machining is already matched the front. Then the object holder can be offset.

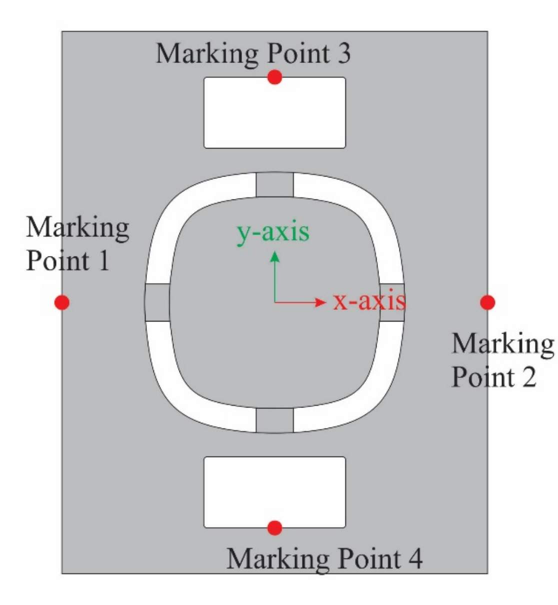


Figure 12. Method 4 settings

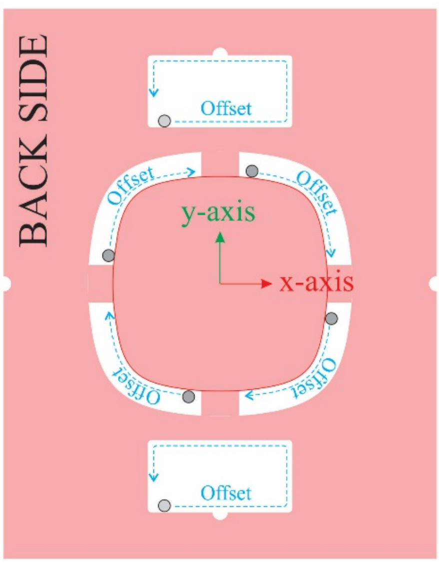


Figure 13. Offset checking procedure

III. Results and Discussions

Each methods was performed three times. The results shown by the three runs for each method were then compared by visual traits, measurements, and the significance of the mismatched mark to the finished end products, and problems that emerged along with the processes. The results for method 1 is shown in Figure 14a in which the mismatched marks can clearly be seen. The results of method 2 (Figure 14b) were similar with method 1. Furthermore, the mismatched marks still appear in the experiment made with method 3 (Figure 14c). Experiments conducted with method 4 shows the best results where the mismatched marks are no longer visible (Figure 14d).

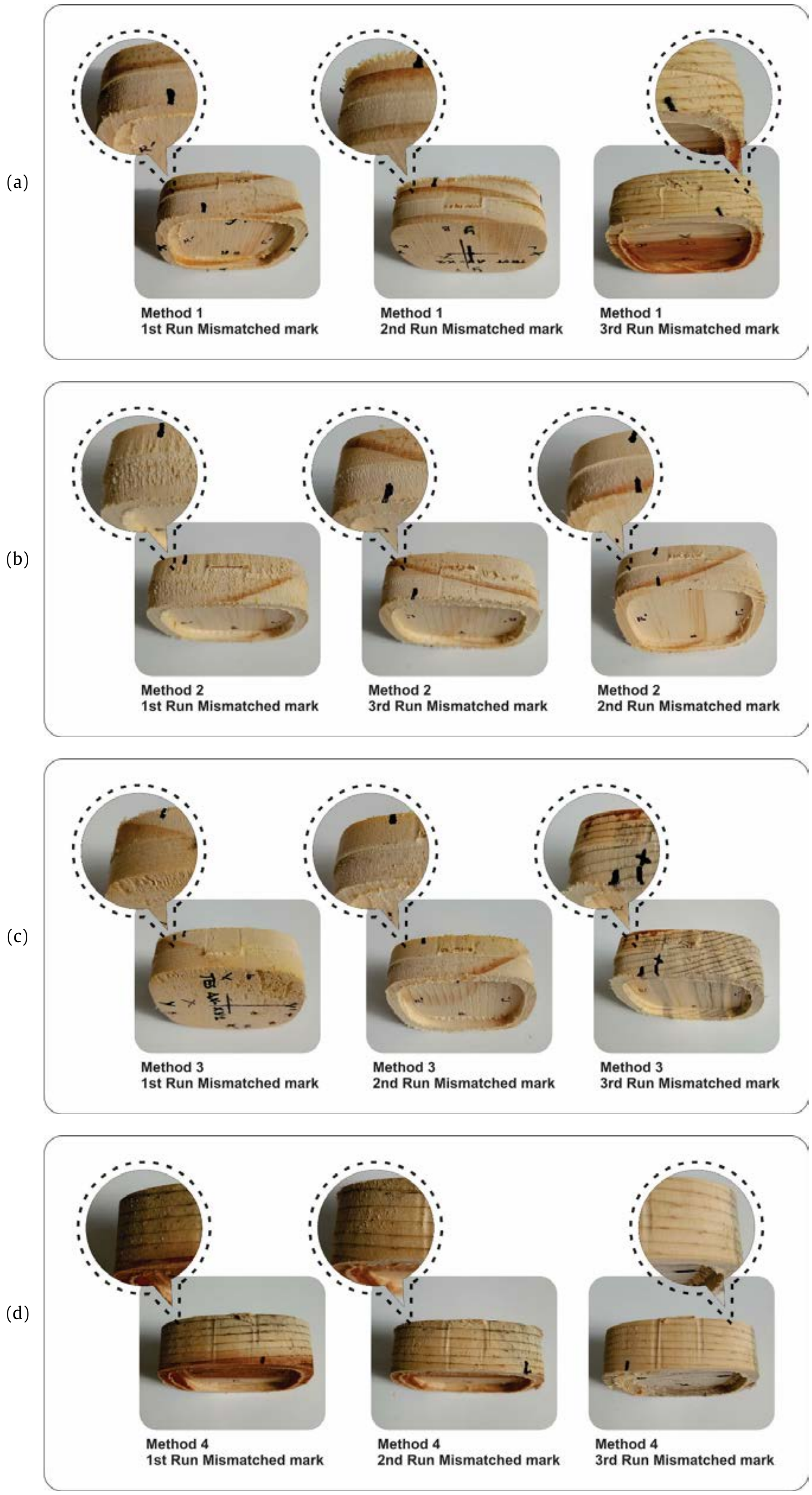


Figure 14. Results of each three runs for each method: (a) method 1; (b) method 2; (c) method 3; and (d) method 4

The comparative results are tabulated in Table 1, Table 2, and Table 3. The first parameter in measuring if the method gives the best result is by qualitatively observing and comparing the mismatched marks between the front and the back-side machining processes results (Table 1). All three-run results done with method 1 show that mismatched marks can be clearly seen. The same traits are also shown in all three runs of each method 2 and method 3. In method 4, the mismatched marks are relatively less visible compared to the results of the other three methods.

The second parameter to determine if the methods give the best results is by measuring the distance of the mismatched position of the front and back machining processes. The narrower the mismatched position, the better the result is. The results of the measurements are tabulated in Tabek 2. In method 1, the average distance of a mismatched position on the x-axis is 0.48 mm, while the y-axis is 0.41 mm. In method 2, the average distance of a mismatched position on the x-axis is 0.42 mm, while the y-axis is 0.45 mm. In method 3, the average distance of a mismatched position on the x-axis is 0.41 mm, while the y-axis is 0.43 mm. In method 4, the average distance of a mismatched position on the x-axis is 0.1 mm, while the y-axis is 0.22 mm.

The distance between a mismatched position of the front-side machining processes and the back-side machining gives a direct result in the quality of the finished end products. The wider the mismatched distance will result in greater efforts to remove the mark by sanding the product's side surface. The more the side is sanded, the more the actual size of the product is reduced; thus, the end size will not be relatively similar to the design. This would be a great problem, especially if the design includes wall features along the outer side of the products. The sanding processes could result in a different thickness of the wall. The significance of the effects of the mismatched marks on the finished end products is tabulated in Table 3. Even though the mismatched marks in all of the results given by all the four methods are removable by the sanding process; since the mismatched marks in methods 1, 2, and 3 are relatively wider compared to method 4, it can be resulted in a width differences if the product design includes wall features along the outer side.

It also needs to be considered if the methods have emerging problems along the process. The problems that emerged along the processes can be seen in Table 4. Method 1 is considered to have fewer problems since the features included in the process are not many. The more features included in the methods, the more problem emerged in the process. Method 4 provides more difficulties during the process, but the problems can be overcome by the last process of the method (by manually adjusting $(x, y) = (0,0)$ and offset checking). But it is worth it since the final results have given the best results, as shown in Table 1, Table 2, and Table 3.

Table 1.
Visual traits comparison

Method	1^{st} run	2^{nd} run	3^{rd} run
1	Clearly visible	Clearly visible	Clearly visible
2	Clearly visible	Clearly visible	Clearly visible
3	Clearly visible	Clearly visible	Clearly visible
4	Almost invisible	Almost invisible	Slightly visible

Table 2.
Measurements comparison on mismatched position

Method	Mismatched distance (mm)					
	1^{st} run		2^{nd} run		3^{rd} run	
	x-axis	y-axis	x-axis	y-axis	x-axis	y-axis
1	0.46	0.30	0.41	0.39	0.58	0.54
2	0.38	0.37	0.38	0.43	0.49	0.56
3	0.20	0.27	0.57	0.66	0.45	0.35
4	0.07	0.15	0.13	0.21	0.11	0.31

Table 3.
Significance of the mismatched mark to the finished end products

Method	Significance of the mismatched mark to the finished end products		
	1^{st} run	2^{nd} run	3^{rd} run
1	Insignificant, removeable with sanding paper, leaving visible thickness differences after sanded	Insignificant, removeable with sanding paper, leaving visible thickness differences after sanded	Insignificant, removeable with sanding paper, leaving visible thickness differences after sanded
2	Insignificant, removeable with sanding paper	Insignificant, removeable with sanding paper, leaving visible thickness differences after sanded	Insignificant, removeable with sanding paper, leaving visible thickness differences after sanded
3	Insignificant, removeable with sanding paper	Insignificant, removeable with sanding paper, leaving visible thickness differences after sanded	Insignificant, removeable with sanding paper, leaving visible thickness differences after sanded
4	Insignificant, almost no further action needed	Insignificant, almost no further action needed	Insignificant, removeable with sanding paper

Table 4.
Problems emerged along the processes

Method	Visual traits
1	No significant problem
2	Setting the material at the correct markings was found to be a little difficult (in *y*(+)), for the view is blocked by the spindle
3	Setting the material at the correct four markings was found to be more difficult than at two markings. It tends to miss one marking (top *y* (*y*(+)) markings)
4	Setting the material at the correct four markings was found to be more difficult than at two markings. It tends to miss one marking (top *y* (*y*(+)) markings)

IV. Conclusion

All four methods examined are possible to be used for the back-side machining. But method 4, which includes the two-point markings on each *x*-axis and *y*-axis with the offset checking method, has given the best results. The method gives the opportunity to check the position of the *x*- and *y*-axis, whether they are already in the precisely desired positions, which cannot be done with the other three methods. The comparison of the results shown by the four methods reveals that in method 4, the mismatched marks are relatively almost invisible compared to the results of the other three methods. In method 4, the average distance of a mismatched position on the *x*-axis is 0.1 mm, and on the *y*-axis is 0.22 mm. The distance is narrower compared to the other three methods. Even though the mismatched marks in all of the results given by all the four methods are removable with the sanding process; but since the mismatched marks in method 1, method 2, and method 3 are relatively wider compared to method 4, it can result in width differences if the product design includes wall features along the outer side. Method 4 is emerging more difficulties during the process, but it is worth to be done since the final results have given the best results compared to the other three methods. The method can be used for SMEs with limited capital capabilities since the method can be done manually with the three-axis milling machine and does not require an additional fourth axis.

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Declarations

Author contribution

R.V. Febriyana: Writing - Original Draft, Writing - Review & Editing, Conceptualization, Experimentation, Formal analysis, Investigation, Visualization, Supervision. R.S. Pernyata: Writing - Original Draft, Writing - Review & Editing, Conceptualization, Investigation, Validation, Photography. D. Andansari: Data Curation, Formal analysis, Resources, Software, Visualization.

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Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] D. Ryfors, M. Wallin, and T. Truve, "Swedish manufacturing SMEs readiness for Industry 4.0," Bachelor Thesis, Sweden: Jönköping University, 2019.
[2] M. Eriksson and O. Ekebring, "Managing a transformation towards industry 4.0: A study within the bus manufacturing industry," Industrial Management Degree Project, Sweden: Karlstads Universitet, 2020.
[3] D. Awari, M. Bhamare, A. Ghanwat, K. Jadhav, and J. Chahande, "Methodology for Selecting Components for Fabricating CNC Milling Machine for Small Scale Industry," *International Journal for Scientific Research and Development (IJSRD)*, vol. 4(11), pp. 168-171, 2017.
[4] S. Vaidya, P. Ambad, and S. Bhosle, "Industri 4.0 – A Glimpse,". *Procedia Manufacturing*, vol. 20, pp. 233-238, 2018.
[5] B. Jayachandraiah, O. V. Krishna, P. A. Khan, and R. A. Reddy, "Fabrication of Low Cost 3-Axis Cnc Router," *International Journal of Engineering Science Invention (IJESI)*, vol. 3(6), pp. 1-10, Jun. 2014.
[6] W. Qin, "Design and Analysis of a Small-scale Cost-effective CNC Milling Machine," Thesis, Illinois: University of Illinois Urbana-Champaign, 2013.
[7] N. Sathyakumar, K. P. Balaji, R. Ganapathi, and S. R. Pandian, "A Build-Your-Own Three Axis CNC PCB Milling Machine," in *Proc. IConAMMA*, 2018, pp. 24404–24413.
[8] P. Bhasin, P. Singh, and S. Singh, "Design and Fabrication of Low-Cost Wood Working Mini CNC Milling Machine for Students Skill Development," *International Journal of Advance Research and Innovation (IJARI)*, vol. 8(1), pp. 30-33, Mar. 2020.
[9] P. Girhe, S. Yenkar, and A. Chirde, "Arduino Based Cost Effective CNC Plotter Machine," *International Journal of Emerging Technologies in Engineering Research (IJETER)*, vol. 6(2), pp. 6-9, Feb. 2018.
[10] S. Patil and S. S. Anasane, "Development of 3-Axis Micro-Step Resolution Desktop CNC Stage for Machining of Meso- and Microscale-Features," in *Advances in Simulation, Product Design and Development (AIMTDR)*, Springer, 2018, pp. 637-652.
[11] Ernest, H. Sutanto, and D. Setyanto, "CNC Milling Portable PM 1035," *International Journal of Applied Engineering Research (IJAER)*, vol. 13(12), pp. 10358-10364, 2018.
[12] S. M. Ali and H. Mohsin, "Design and Fabrication of 3-Axes Mini CNC Milling Machine," presented at the 1st International Conference on Sustainable Engineering and Technology (INTCSET), Baghdad, Iraq. 2020.
[13] R. Ginting, S. Hadiyoso, and S. Aulia, "Implementation 3-Axis CNC Router for Small Scale Industry," *International Journal of Applied Engineering Research (IJAER)*, vol. 12(17), pp. 6553-6558, 2017.

[14] A. Estiyono, A. Kurniawan, and A. D. Krisbianto, "Prototipe mesin CNC 3 axis sederhana untuk IKM mainan edukasi berbahan kayu," *Jurnal Desain IDEA*, vol. 17(2), pp. 17-20, Oct. 2018.
[15] K. Bangse, A. Wibolo, and I. K. E. H. Wiryanta, "Design and fabrication of a CNC router machine for wood engraving," presented at the International Conference on Applied Science and Technology on Engineering Science (iCAST-ES), Bali, Indonesia, 2019.
[16] S. H. Suh, W. S. Jih, H. D. Hong, and D. H. Chung, "Sculptured surface machining of spiral bevel gears with CNC milling," *International Journal of Machine Tools and Manufacture*, vol. 41(6), pp. 833-850, May 2001.
[17] S. Suh and J. Lee, "Five-Axis Part Machining With Three-Axis CNC Machine and Indexing Table," *ASME Journal of Manufacturing Science and Engineering*, vol. 120(1), pp. 120–128, Feb. 1998.
[18] D. A. Axinte, S. A. Shukor, and A. T. Bozdana, "An analysis of the functional capability of an in-house developed miniature 4-axis machine tool," *International Journal of Machine Tools & Manufacture*, vol. 50(2), pp. 191-203, Feb. 2010.
[19] E. E. Wai and S. S. Aung, "Design and Implementation of 4-Axis CNC Machine," *International Journal of Recent Innovations in Academic Research*, vol. 3(8), pp. 60-71, Aug. 2019.
[20] L. N. L. de Lacalle, A. Lamikiz, J. A. Sánchez, and M. A. Salgado, "Effects of tool deflection in the high-speed milling of inclined surfaces," *International Journal of Advanced Manufacturing Technology*, vol. 24, pp. 621-631, Nov. 2004.
[21] S. N. Phokobye, I. A. Daniyan, I. Tlhabadira, L. Masu, and L. R. VanStaden, "Model Design and Optimization of Carbide Milling Cutter for Milling Operation of M200 Tool Steel," *Procedia CIRP*, vol. 84, pp. 954-959, 2019.
[22] S. Hu, M. Zhang, Y. Cui, R. Xue, and Z. Yang, "Accuracy Enhancement with Processing Error Prediction and Compensation of a CNC Flame Cutting Machine Used in Spatial Surface Operating Conditions," *Journal of Engineering and Technological Sciences*, vol. 49(1), pp. 75-94, Apr. 2017.
[23] M. Soori, B. Arezoo, and M. Habibi, "Accuracy analysis of tool deflection error modelling in prediction of milled surfaces by a virtual machining system," *International Journal of Computer Applications in Technology*, vol. 55(4), pp. 308-321, Aug. 2017.