Mini CNC Design to Increase Students’ Programming and Control CNC Competencies

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Abstract. Practical tools used in learning must support and adapt to the needs of the Industrial Revolution 4.0 era with the characteristics of working automatically, 3D printing, internet-based work of things (IoT) and Data of Things. One practice tool that works with these principles is a CNC machine. Mini CNC design that has been made has been equipped with modern computing technology. Mini CNC learning media aims to make students not only skilled in terms of operating the machine, but students can develop their skills in the design and programming of a CNC machine. This research was conducted based on the ADDIE model, namely Analysis, Design, Development, Implementation and Evaluation. The results of the design and manufacture of IoT-based Mini CNC 3D printers for learning media consist of designing hardware and software. Linearity test results showed there was no significant difference between the setting value and the measured value of the results of the work process of the tool and being able to do the cutting process from wood, fiber or aluminum, so that the Mini CNC was suitable for use as a learning media.

1. Introduction
Graduates competency of Vocational High School is currently faced with meeting the needs of the workforce in the Industrial Revolution Era 4.0. The process of producing goods and services using digital technology is better known as "Industry 4.0". This term was first known in Germany in 2011. German Chancellor, Angela Merkel, introduced the term at the WEF 2015 annual meeting. Industry 4.0, which is integrating the online world with industrial production. The current industry 4.0 applications include fields such as: digital printing 3D, routers, Internet of Things (IoT), smart factories, robotics to innovative systems of production of goods and services integrated with information and communication technology (ICT) [1].

The availability of instructional media is still limited and there is no development of suitable learning media in Vocational High Schools, especially in schools that are located far from urban areas, so that basic competency goals cannot be achieved. This has an impact on learning outcomes that are still low on average with minimal completeness criteria that have not been achieved [10]. The competency of Vocational High Schools graduates who supported the era of the Industrial Revolution 4.0 can be achieved one of them by increasing psychomotor learning which is reflected in the learning practices in school. In the success of learning practice in schools, there are several supporting factors that should be met by a school. One of these factors is the facilities related to school facilities and infrastructure, especially in the field of media for learning or practice equipment. Practical tools used in learning should support and adapt to the needs of this era with the characteristics of working automatically, 3D printing, work based on the Internet of Things (IoT) and Data of Things. Vocational High Schools try to improve
the quality of graduates by improving facilities and infrastructure in the form of laboratory learning practice and CNC machining. The aim is to produce graduates who have the skills to operate CNC, especially for industrial processes [9].

One of the practical equipment that works with the principle as above is a CNC machine. The Mini CNC design that was made has been equipped with modern computing technology. CNC learning media aims to make students not only skilled in operating the machine, but students will also develop their skills in designing and programming to make an object. Design using relatively inexpensive materials so that this learning media can be used in schools that need to improve student skills.

1.1. Mini CNC
CNC is one where the function and movement of machine tools is controlled through a program that is prepared which contains alphanumeric-coded data. CNC can control the movement of the workpiece or tool, input parameters such as feed, depth of cut, speed, and functions such as turning on / off the spindle, turning on / off the cooler. There are many types of CNC machines. Common CNC machines are two-axis and three-axis. The two-axis machine can move only vertically and horizontally which are the X and Y axes. The three-axis machine can make movements starting with the three main axes namely the X, Y and Z axes. The Z axis is paralleled with a shaft [5].

CNC machine operations begin by gathering data from programming then extracting it using Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM) programs. The programs generate computer files and then extract commands to operate the machine. The program will be transferred through the post-processor and then loaded into the CNC machine to start machining. The flow of CNC machine operations is shown in figure 1.

![Figure 1. CNC Machine Operation Process [4]](image1)

CNC is a system. In a CNC machine system, there are 4 main components namely mechanical design, drive modules, system software and Automatically Programming Tool (APT) postprocessor. Mechanical design system, this part is the hardware part of the machine which is part of the frame. Drive system, the command signal is received from the microprocessor. Microprocessors consist of motors, amplifier units and power supplies. For software systems, the software generates a program to the CNC machine to start the movement of tools and workpieces. For APT post-processors, it was developed to produce G-codes and M-codes that can be used by CNC machines.

![Figure 2. CNC machine workflow [4]](image2)
CNC applications cover both machine-tool and non-machine-tool areas. In the machine-tool category, CNC is widely used for lathes, drill presses, milling machines, milling units, lasers, sheet metal processing machines, tube bending machines and so on. Highly automated machine tools such as turning centers and machining centers that automatically change cutting tools under CNC control have been developed. In the non-machine-tool category, CNC applications include welding machines (arcs and resistances), coordinate measuring machines, electronic assembly, laying tape and filament machines for composites and so on [2].

The benefits of CNC machines are (1) high accuracy in manufacturing, (2) short production time, (3) greater manufacturing flexibility, (4) contour machining (2 to 5-axis machining), (5) reduction in human error. The disadvantages include high costs, maintenance, and the need for skilled programmers [6].

This research includes the design, manufacture and application of three-axis mini CNC machine tools to meet the needs of practical equipment in Vocational High School.

Design of Frame Construction in Prototype 3 Axis CNC Milling Machine, which uses electrical components used in the form of power supply, DC servo drive, DC stepper motor, Break of Board produces a prototype of a small CNC Axis 3 milling (mini) as a medium of teaching, training and research [8]. Transfer of Project Development Training To Vocational High School Students To Three Axis Mini CNC Router Design: An Applied Study, has the objective to determine the success of project development and training provided to students [4]. In his research, theoretical and practical training is given to students on the theoretical calculations of machine construction, machine design and manufacturing, the stage of system assembly and analysis and system studies. As a result of the training, students were asked to design and make a three axis CNC mini router. During the design and manufacturing process, the required technical support is provided to students who have problems in making the project. The results of this study, it has been seen that students have successfully transferred the theoretical knowledge they received to the design and manufacture of CNC routers. After the manufacturing process is complete, the sample is processed and the functionality of the mini CNC router machine is tested and the results obtained [4].

1.2. Era Revolusi Indsutri 4.0
The Industrial Revolution Era 4.0 produced an intelligent factory where all used the Internet of Think (IoT). IoT is a concept such as industrial machines, electricity generators, vehicles, household appliances, to wearable devices that are interconnected through networks to exchange in real time [3]. The special characteristic of the Industrial Revolution Era 4.0 is that it occurs through communication between humans, machines and their resources. The fourth industrial revolution was marked by a paradigm shift from being centrally controlled to a decentralized production process. The world of education must also be able to evolve in accordance with the development of existing technology and must be able to predict the needs of labor and technology in the industry. Education must be relevant to current and future employment. In the sense that education must be able to adapt and be flexible both teachers, students, as well as existing facilities and infrastructure. As Dagli and Durmus stated that "Vocational and Technical Education should provide students with appropriate information equipment in accordance with the requirements of the advanced age in their general skills ...... provides a practical training in laboratories equipped with new technology and cooperates with all common working partners "[5].

Major changes are needed in the world of Education to support the industrial revolution 4.0, to realize this, it is necessary to have facilities including infrastructure in learning, namely practical tools as a support for the achievement of education in the industrial revolution era 4.0. Attention to school facilities such as practical tools used in learning are factors that have a strong influence on output. As Ekundayo and Haastrup said in their research journal, "Availability of school physical facilities and the conduciveness of the school learning environment have been said to be potential factors influencing students' achievement in the affective and the psychomotor domains" [6]. The results of this study are expected to produce learning media in the form of mini CNC that can be used in improving the programming and control competence of CNC machines in Vocational High Schools. Competencies
that can be supported are competencies in the subject of Mechatronic System Control Engineering. The mini CNC made is expected to meet learning standards in the Industrial Revolution 4.0 era, especially in the IoT section.

2. Research Method
This research uses the Research and Development method. The study was conducted based on the ADDIE model namely Analysis, Design, Development, Implementation and Evaluation. The process carried out at the analysis stage is to identify what competencies are needed by SMK students in terms of CNC programming and analyzing material requirements, surveying the type of material / equipment, and selecting the appropriate material quality. The design phase is carried out by designing a Mini CNC in accordance with the requirements at the analysis stage. This design is done in the form of hardware and software. The development phase is carried out by making the Mini CNC starting from making and assembling its hardware consisting of mechanical and electronic parts, then installing and connecting the software to the hardware that has been made. The setting is also done on the software so that it can communicate with the hardware that has been prepared, then test the mini CNC performance that has been made. Implementation phase, in this stage the implementation of learning the CNC programming using 3D Printed Mini CNC is implemented. Evaluation is done to get improvements from the implementation that has been done. Improvements in hardware, software, lesson plan and user manuals are carried out at this stage. Data retrieval is done in two ways, namely observation used to get data about the competencies required by vocational students in programming and controlling CNC, and testing the performance of tools that have been made is also carried out in the process of taking data by taking the parameters of the tool that will produce specifications and manuals.

3. Research Results and Discussion
The analysis phase is carried out by identifying what competencies are needed by SMK students in terms of CNC programming, generating data based on the Vocational Curriculum of the Mechatronics Engineering Program. Mini CNC can support the achievement of competency skills in the Mechatronic System Control Engineering Subjects, namely related to the scope of control techniques and regulatory systems, open and close loop control systems, drawing method in control techniques, analog to digital converters and digital to analog converters, logic circuit control and the workings of control circuits with electronic media using analog and digital electronic components, as well as brushed and brushless DC motor controller circuits. All components in the mini CNC support this competency.

The implementation of Mini CNC design is in accordance with the requirements at the analysis stage. This design is done in the form of hardware and software. The design of work flow chart is as follows:

![Flowchart of a mini CNC work process](image)

**Figure 3.** Flowchart of a mini CNC work process
Development of Mini CNC uses Raspberry PI Mini PC with Linux Operating System to run previously created .gcode files. Raspberry PI Mini PCs along with LinuxCNC can control the spindle or laser on or off to spindle or laser speed settings. Mini PCs along with LinuxCNC can control the motion and speed of each Stepper Motor until knowing the maximum working distance of the machine using the Limit Switch sensor. In addition, Mini PCs along with LinuxCNC can be controlled through the IoT (Internet of Things) program that uses python programming language, HTML5, and websocket connections so that this machine is called the IoT-based CNC Mini Low Cost Machine. The process flowchart is used as a basis for making software. The software used is based on the Linux operating system using Machinekit.

The development stage produces a system of connections between hardware components as shown in figure 5.

![Figure 4. 3D Printed Mini CNC design](image)

![Figure 5. Connection between components on a mini CNC](image)
stepper motor driver, so that the stepper motor rotation can be set based on commands from the Mini PC. BOB also has a terminal that is connected to the limit switch where the limit switch is installed at each axis limit. The limit switch will limit the working area of the CNC machine. If the limit switch is active/pressed, BOB will instruct the motor on that axis to stop rotating because the position is already at the maximum point of the axis.

The result of software development used in developing mini CNC is Machinekit where the software is in the Linux operating system. The Graphical User Interface (GUI) display of the LinuxCNC Machinekit is shown in figure 6.

![Figure 6. Display of the Machinekit GUI](image)

**Table 1. Buttons in the Toolbar group**

| Buttons | Function                                      | Buttons | Function                              |
|---------|-----------------------------------------------|---------|---------------------------------------|
| [X]     | Shutting down the system in an emergency      | [+]     | Zoom in                               |
| [O]     | Turn on the machine                          | [--]    | Zoom out                              |
| [File]  | Open G-Code file                             | [Z]     | Display top view                      |
| [Reload] | Reload current file                         | [N]     | Rotate the top view                   |
| [Run]   | Run the program file to be executed          | [X]     | Display side view                     |
| [Run]   | Run the next line file program               | [Y]     | Display front view                    |
| [Pause] | Pause the execution of program files         | [P]     | Isometric display                     |
| [Stop]  | Stop executing program files                 | [Bell]  | Toggle between Drag and Rotate Mode   |
| [Split] | Toggle Skip lines with "/"                   | [Brush] | Clean the application display         |
| [Optional Pause] | Toggle Optional Pause                       |         |                                       |
Table 2. Buttons in the Control group

| Buttons | Function | Buttons | Function |
|---------|----------|---------|----------|
| X       | Y        | Adjust the sledding motion of each axis | Adjust the direction and speed of the spindle rotation. |
| +       | -        | Set the work speed of the machine        | Spindle rotation indicator |
| Z       |          | Display program code                     | Time indicator when working |

The implementation is carried out with the application of CNC programming learning using 3D Printed Mini CNC. The implementation test is carried out in the course of Maintenance and Repair of CNC Mechatronics Engineering Education Study Program where students are asked to identify material requirements, arrange materials, identify work processes, test by making a product in the form of a Print Circuit Board (PCB).

Students in the learning process are asked to produce a product in the form of a Print Circuit Board (PCB). This PCB is obtained from a design created using PCB design software that produces a PCB image file. The image file is then converted into numerical codes used in CNC machine processing. The product results from manufacturing PCBs using mini CNC are shown in Figure 7.

![Figure 7. The results of making PCB using mini CNC](image)

The evaluation phase is carried out to get improvements from the implementation that has been done. Linearity test is carried out in this stage to test whether there is a difference between the value of the amount of input (setting) on each axis equal to the results of the work (measured value) mini CNC.

Table 3. Data on the results of the mini CNC linearity test

| Positive X-axis (mm) | Negative X-axis (mm) | Positive Y-axis (mm) | Negative Y-axis (mm) | Positive Z-axis (mm) | Negative Z-axis (mm) |
|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| Setting              | Measured Value       | Setting              | Measured Value       | Setting              | Measured Value       |
| 30                   | 30                   | 30                   | 30                   | 30                   | 10                   |
| 60                   | 60                   | 60                   | 60                   | 60                   | 20                   |
| 90                   | 90,4                 | 90                   | 90                   | 90                   | 30                   |
| 120                  | 120,4                | 120                  | 120                  | 120                  | -                    |
| 150                  | 150,4                | 150                  | 150                  | 150,5                | -                    |
From the results of the linearity testing, it can be seen that in general there is no significant difference between the setting value and the measured value either in the X-axis, Y-axis or Z-axis processing, while for the Z-axis values ranging from 30 to 90 mm. The value of this setting is adjusted to the maximum length of each axis which then describes the maximum dimensions of the mini CNC. Based on the linearity value, the dimensions of the tool are in the range of 150 mm x 150 mm x 90 mm and are in the form of beams.

Figure 8. Dimensions of mini CNC work

This can be interpreted that the mini CNC that has been developed can serve the design of the maximum dimensions of 150 mm x 150 mm x 90 mm. The material used in the trial implementation using a cutting tool made from high-speed steel (HSS) can make the cutting process from wood, fiber or aluminum.

4. Conclusion

Competencies that can be supported from a Mini CNC 3D Printer Learning Media are competencies in the subjects of Mechatronic Control System Engineering related to the scope of control engineering and control systems, open and close loop control systems, depiction methods in control techniques, analog to digital converter and digital to analog converter, logic circuit control and the workings of a control circuit with electronic media using analog and digital electronic components, as well as a brushed and brushless DC motor controller circuit where all components in the mini CNC support this competency. The design and manufacture of IoT-based Mini CNC 3D printers for Learning Media consists of hardware and software design.

The performance of the 3D IoT-based Mini CNC printer can be seen from the results of the linearity test where there is no significant difference between the setting value and the measured value of the tool performance test results and is able to do the cutting process from wood, fiber or aluminum, so that the Mini CNC is feasible to be used as a means in learning. Implementation in learning from the Mini CNC 3D printer is carried out in the course of maintenance and repair of CNC on Mechatronics Engineering Education study programs where students are asked to identify material requirements, arrange materials, identify work processes, test by making a product in the form of a Print Circuit Board (PCB).

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