DIGITALIZING CONVENTIONAL MACHINES: A COMPLETE PRACTICAL IMPLEMENTATION SOLUTION

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Increasing productivity is all factories want to do. The purchase of new and modern machines requires a huge amount of cost and trained human resources. Meanwhile, traditional machines have the advantages of low investment costs, efficiency in roughing machining, and low labor costs. However, one of the disadvantages of traditional machines is that the machining surface is poor, and tool wear occurs more frequently. To overcome these disadvantages, a proposed solution is to digitize traditional machines. The authors have implemented a digitizing project on a milling machine by connecting a motor controller and sensors, reading and transmitting data to the center, and displaying it. The information obtained will help improve the machining process and limit the risk of failure.

KEYWORDS

Digitalizing conventional machines, sensors, data transmission, industry 4.0, graphical user interface, smart manufacturing

1 INTRODUCTION

Industry 4.0 (I4.0) is becoming more and more urgent for companies and factories. The characteristics of I4.0 can be listed as flexibility of the production process, the ability to customize and optimize the production process, and a high level of automation. Many studies have shown the main technologies in smart manufacturing including CPS (Cyber Physical System), IoT (Internet of Things), Cloud Computing, Big data (or data analysis), Robots, and Sensors [1][2].

Not only large companies, small and medium enterprises also face the urgent need of improving product quality and efficiency. Industry 4.0 is therefore the path and goal that businesses aim for. However, the process of this digitalizing in small and medium enterprises is rather slow due to a lack of knowledge about it, including the cost, complexity, economic benefits, and technologies [3]. Building a new factory with 4.0 standards is almost impossible because it requires a huge amount of money and takes a very long time. Instead, with the existing infrastructure, upgrading the factory by enhancing the ability to automate, digitize, transmit information, monitor and control flexibly is a better choice for these enterprises. Most of today's small and medium-sized factories do not have MES systems. Machines operate discretely without connectivity or exchanging information with each other. Some factories are still using traditional machines and hand-operated equipment that has not been digitized at all.

In developing countries, with limited funding and low labor costs, these traditional machines are still the optimal solution in small and medium-sized factories. However, with the appearance of more advanced and modern machines in the world, traditional machines face the risk of a lack of replacement equipment when worn or damaged. At the same time, there are fewer and fewer people who have experience in repairing old machines. Therefore, maintaining traditional machines becomes trouble and might consume a large part of the factory's budget. One of the solutions to reduce repairs and maintenance costs is to upgrade the machine to a higher-level-information-transmit. It means all the statuses of these machines must be recorded and sent to the data center. The first mission is to digitize information about the machine, then to create the ability to communicate and transfer data between machines, and finally to monitor and manage the machine with user interface software.

There have been many studies related to upgrading existing machinery systems to 4.0 in the world. João Cunha and colleagues built a control system and linked existing equipment, which was operating separately, into a complete communication system including lathes and milling machines, mobile robots, assembly, and quality control stations [4]. The system's data is uploaded to the cloud. Similarly, Hanna Jónasdóttir et al. have also designed an industrial IoT interface called BAUTA along with a system of techniques that allows the collection and monitoring of machine data by non-invasive methods [5].

Meanwhile, Chawki El Zant et al. have introduced a method to improve the flexibility of manufacturing operations, including robot trajectories, processing, and quality control. The method of this group is to convert a stationary production system into one that can be easily moved using MES software. Specifically, the authors still keep the PLC control system in the machines, but move the decision-making process to the MES software, not in the PLCs [6].

Quite apart from CNC machines and robots, some studies have been conducted to find solutions for upgrading traditional mechanical machines, which are already outdated. Sunidhi Dayam and colleagues have improved conventional machines by attaching low-cost sensors to lathes [7]. Draw-wire sensors are mounted on the headstock and cross-slide, while the force sensor is placed on the tool post.

In a similar study, with conventional and CNC machines, A. Setiawan et al. used computer technology, the internet, and a network of sensors to monitor the manufacturing process. This sensor network includes temperature sensors, vibration sensors, and power sensors. The authors also added RFID sets to help control the location and level of product completion during the production process. The information obtained from the sensor system will be transmitted via a wifi signal to the data center. Information in the production process is therefore fully monitored, which is a prerequisite for upgrading to a smart factory.

In another direction, Christopher Prinz et al. introduced another problem of Industry 4.0 which is human resources. They mention about people who have not been trained or thoroughly prepared in advanced production [8]. Therefore, the authors propose the concept of “learning factories” which is a miniature factory for learning and training. In this miniature factory, only basic equipment is needed including lathe machines (mechanical and CNC), milling machines (mechanical and CNC), a drilling machine, a saw machine, and 2 assembly lines with 7 small stations. The software that includes the MES system is used and data is collected from the machines through the OPC-UA. The main purpose of the factory is to provide a near-realistic production environment for students and trainers.

Research around the world, as described above, has shown that it is possible to upgrade conventional machines and equipment. However, these studies only offer options and propose solutions, without going into details. For example, in the study of H. Jónasdóttir, the mounting of temperature and vibration sensors as well as criteria and standards for mounting were not mentioned [5]. Similarly, the criteria and standards for setting up BAUTA software are not mentioned. In the study of A. Setiawan, there is no explanation about the electrical energy sensor, how it is used, and how it is converted [9]. On the way toward smart manufacturing, the need to upgrade, digitize machines, and build controllers and communication systems by ourselves is essential.

Before going into digitalizing conventional machines, we need to understand that data from sensors need to be collected through a main controller, usually a Programmable Logic Controller (PLC) [10][11]. This data will then be stored in a server to be accessed or analyzed by other software.

With the main goal of digitizing and upgrading the information system for existing traditional machining machines, in order to achieve higher efficiency in the production and maintenance process, the following issues are raised:

- Digitizing the system by attaching sensors, upgrading the transmission system, constructing electrical systems, and controlling by computer.
- Collect information from sensors and store it in a data center. This data can be used to analyze performance, productivity, and target quality improvement.

In this digitalization project, the authors plan to work with 4 conventional machines, including 2 lathes and 2 milling machines. However, within the scope of this paper, the authors only present the digitization work with a conventional milling machine demonstrated in Fig. 1. The goal of the project is to help businesses improve to increase machine efficiency, increase management efficiency and save costs.

Figure 1. The milling machine Shizouka VHR-A used in the digitalization project

2 MATERIAL AND METHODS

In this project, the authors plan to make three main upgrades: The first work is to monitor the machine's working time, the second thing is to control spindle speed, and the last duty is to attach sensors to measure the machine's current consumption, level and temperature of the coolant.

2.1 Monitoring the working time

In manufacturing, overall equipment efficiency (OEE) is a very important indicator, calculated by:

$$OEE = A \cdot P \cdot Q \tag{1}$$

where:

A = Run Time / Planned Production Time

P = (Ideal Cycle Time × Total Count) / Run Time

Q = Good Count / Total Count

Planned Production Time and Ideal Cycle Time are pre-planned values. Total Count and Good Count are the total amount of products produced and the total quantity of products that meet the requirements, respectively, and will be counted by people. Thus, only Run Time is the variable that needs to be measured automatically during the production process. Therefore, the authors propose to measure this value by sending an on/off signal to the data center as soon as this happens. Having information on when to turn on and off the machine, Run Time can be easily calculated.

2.2 Control and monitor the spindle speed

Spindle speed is one of the important factors in machining. Taylor's Tool Life Equation is a formula that describes the relationship between cutting speed and tool life, expressed as:

$$V \cdot T^n = C \tag{2}$$

where V is cutting speed, T is tool life, n is a constant value called tool life index, and C is a machining constant.

According to this Taylor's Equation, cutting speed is inversely proportional to tool life. Going into detail, if the spindle speed is too low while the feed rate is high, it can cause a tool break. If the spindle speed is too high, the tool is overheated and its life will be reduced. In traditional milling machines, only 8-speed levels are selectable. This simplifies fabrication and operation but reduces flexibility. Therefore, the team improved the system by integrating a 3-phase inverter to control motor speed. This improvement is to help select the most optimal speed for the spindle motor.

To choose the optimal spindle speed, it is necessary to compare the actual machining performance, product quality, and tool life. Therefore, in the machining process, it is significant to record the values of the spindle speed. Data is the basis for analyzing and finding out the causes of reduced tool life and surface roughness, thereby providing solutions for quality improvement. The authors plan to attach a sensor to recognize the spindle speed and store this information for later data analysis. There are many types of sensors that can be selected such as optical sensors, magnetic sensors, capacitive or inductive sensors. However, through testing, the optical sensor has high accuracy and less electromagnetic interference.

2.3 Measure other parameters

Coolant is one of the main things to consider when operating a milling machine for a long time as it helps to decrease the temperature during processing. It is also used to flush small abrasive particles from the machining area. Composition, temperature, and coolant level are the three most important factors of coolant. After a period of processing, the oil sticks to workpieces, chips, and tools, then the coolant composition will change as oil density decreases. Operators usually look at the quality of the machined surface finish to check whether the oil density is too low. In small and medium factories, adding oil or lubricant is implemented following a plan or when a lack of oil is detected by the operator. Using sensor vision to check the quality of the surface finish is difficult and not economical. Instead, by getting information on the working time of the machine and the time of last adding oil, we can indicate the next time of adding oil and water to the coolant. The coolant level needs to be checked after a period of time. If the coolant level is too low, it won't be enough, but too high can cause leaks and seepage. Too high coolant temperature can be evidence showing that there is a problem with the machining process. By using an ultrasonic sensor and thermal sensor, coolant level and temperature information can be collected.

In production, the electric energy consumption in the operation of the system is the part that cannot be ignored and can be calculated by the formula:

$$E = P \cdot T \tag{3}$$

where E is electric energy consumption (Wh), P is watts (W) and T is working time (hour). The working time was mentioned in section 2.1. Wattage can be calculated using the formula:

$$P = \sqrt{3} \cdot U \cdot I \cdot \cos(\varphi) \tag{4}$$

where U and φ are the voltage and phase difference between U and I, respectively, and are available parameters. I is the current and should be measured by placing a current sensor in the electrical system.

By collecting information on wattage, the spindle torque T (Nm) is also calculated from the spindle speed and wattage according to the formula:

$$T = \frac{9550 \cdot P}{n} \tag{5}$$

where n is the spindle speed (round/minute), P is measured in watts (W). Based on this torque, the operator could evaluate the compatibility among the feed rate, spindle speed, and material properties of the workpiece. This could prevent breaking up or wearing tools during machining and maintain accuracy by taking corrective action for the wear of the cutting tool.

3 IMPLEMENTATION

This section presents the digitization process for the milling machine. The Shizouka VHR-A milling machine was selected for testing the method mentioned in section 2.

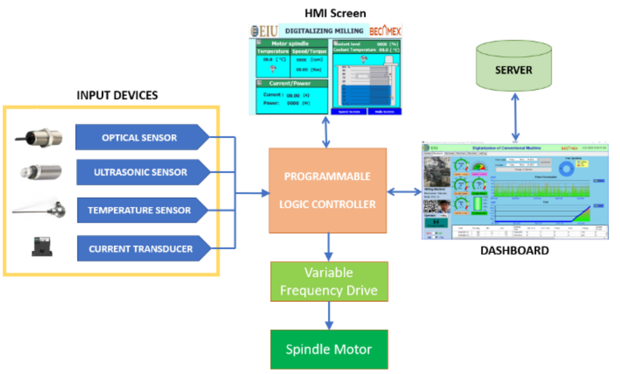

Figure 2. Framework for the conventional milling machine Shizouka VHR-A

A sketch of the machine is shown in Fig. 3. To collect the operating information of the milling machine for monitoring and control purposes, four sensors are installed on the milling machine. Fig.3 illustrates the positions of where to put equipment into the machine. An optical sensor is mounted onto the gearbox of the main motor to measure the speed of the spindle. A temperature sensor is installed in the coolant reservoir to measure the temperature of the coolant. An ultrasonic sensor is installed in the coolant reservoir to measure the coolant level. A current sensor is installed on the power line inside the electrical cabinet of the machine to measure the current of the machine. A three-color signal tower light is mounted on the top of the machine to indicate the status of when the machine is powered on and when the machine is in operation. All measured data from sensor devices are collected and processed and then displayed on the operational screen on a Human machine interface (HMI). The HMI is mounted on a control panel to provide operators with the ability to accurately monitor the operating values of the machine parameters and flexibility in setting control parameters. The spindle speed is controlled by a frequency inverter in the electrical cabinet and altered by changing settings on the HMI screen or the dashboard.

Tab.1 lists the different types of sensors used and the connection between them with the main controller. The optical sensor is connected to an amplifier and the binary signal output from the amplifier is read using a high-speed counter of the PLC. The signal from the temperature sensor goes to a resistance temperature detector (RTD) module of the PLC and is translated to a 16-bit value. The ultrasonic and current sensors are connected directly to an analog-to-digital-converter (ADC) module and data from these sensors is collected in the form of 16-bit values.

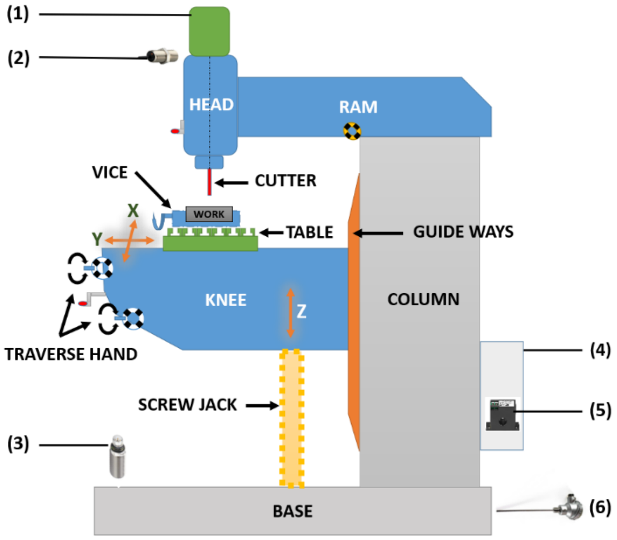

Figure 3. The sketch of the conventional milling machine Shizouka and equipment added to it. (1) Spindle motor. (2) Optical sensor. (3) Ultrasonic sensor. (4) Electrical cabinet. (5) Current transducer. (6) Temperature sensor

Table 1. Device hardware selected for the conventional milling machine Shizouka VHR-A.

Device	Object Measurement	Resolution/ Limitation	Connection
Optical sensor	Rotation of spindle motor	Resolution: 0-20 KHz	Connect to PLC through an amplifier
PT100 temperature sensor	Temperature of the coolant Temperature of the spindle	Input: 0-250ºC Output: 16-bit value	Connect with module RTD of the PLC
AC current transducer (CT)	Electrical current of the machine	Input: 0-50A, Output: 4-20mA	Connect with module ADC of the PLC
Ultrasonic sensor	Level of the coolant	Input: 0-15cm Output: 0-10V	Connect with module ADC of the PLC

A dashboard is a graphical user interface (GUI) demonstrated in Fig. 4 and consists of two main parts: The first part on the left is the machine name and the operator. The second part on the right is the machine's operating parameters which are displayed visually. This dashboard is created by a free software called Visual Studio Community. Data from the machine will be stored in a Microsoft SQL server.

Going into details, in part one, at the top is the image of the machine, along with the manufacturer's name and model of the machine. Next below is the operator's information which includes name and picture. The software collects data about the main responsible person, for example, which machine he uses and his working time. This information helps the manager to visually recognize current operators as well as trace history.

The system also allows changing the operator by double-clicking "Change Operator". This allows other people to use the machine, but with the condition that it has to be approved by the manager, and manage the use time of each person. Therefore, any problems caused by the operator can be traced back from the stored database.

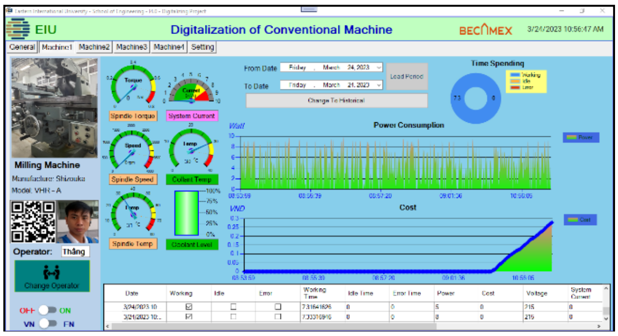

Figure 4. The dashboard used in this project

In the second part, the information received from the sensors mounted on the machine will be displayed on the screen. This information includes spindle speed, spindle torque, machine current consumption, coolant temperature, and coolant level.

The objective of collecting information is to give warnings if the value is lower or higher than the threshold that has been set previously. In addition, the signal on/off the machine as well as on/off the spindle motor is also transmitted to the server. As a result, data about the machine's operating time as well as its energy consumption will be recorded. These data will be used as the basis of machine condition analysis, and calculation of OEE. Since all data is stored on the server, in case of any problem, it is more convenient and easier to access the database to find the cause of the problem.

The GUI software can also reload information from the database over a period of time, allowing this data to be displayed on the screen, for example, energy consumption and estimated power costs. This will help managers to have a more intuitive view of the machine's operating history, operating time, downtime, or failure time, and can compare power consumption between different days or periods of time.

4 CONCLUSIONS

The paper describes a method of applying controllers, sensors, and information technology to increase the efficiency of traditional machining machines. For testing, the system needs to be applied and machined in reality as well as received feedback from the factory. This phase will be done in the next step. Currently, the project has completed its initial goal consisting of online collecting and displaying important parameters of traditional machines, increasing the number of choices in the machining process, and providing necessary warnings.

On the way to transforming the industry from labor-intensive to technology-intensive, the initial results of the project are the basis for the development of advanced digitalizing systems. Next time, the project will be expanded further with the installation of PLC controllers for all types of conventional machines and at the same time digitizing and connecting these machines with CNC machines and robots. The big picture is a complete showroom for businesses to visit, study, be trained, and be encouraged in the transformation towards green and smart manufacturing.

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