Data-driven digital twin model for predicting grinding force

B Qi and H-S Park
University of Ulsan, Department of mechanical engineering, Ulsan, South Korea

E-mail: bowen.niceday@gmail.com

Abstract. Digital twin gives a new approach for predictive and monitoring of manufacturing machines which can consider the influence of working condition on grinding wheel and application of prediction. In this article, we develop methodology for grinding force prediction using digital twin approach, with the vertical double side grinding machine performing the required work while connecting the PLC program. The proposed approach integrates the information obtained from sensor data, physic models, and operational of system to establish the grinding machine model. Data driven modelling and quantification of the model form uncertainties associated with the resulting reduced order models. Simulation results show the proper connection between models and communication. The digital model was programmed to exactly match the operation of the physical system.

1. Introduction
Digital twin gives an approach to manufacturers to gain a clearer picture of real-world performance and operating conditions of a manufacturing asset via near real-time data captured from the asset and make proactive optimal operation decisions [1-3].

Grinding is one of the most common precision machining methods because of its high machining efficiency and good finish quality. During the grinding process, the wheel topography continues to change based on the wheel-workpiece material combination, wheel specification, process parameters.

However, these continuous changes in the wheel topography lead to a glazed condition of the grinding wheel over the grinding process. At this condition, the grinding wheel loses its cutting ability and the process is dominated by rubbing or plowing mechanisms. These mechanisms lead to cutting force increased and affect the surface quality of the part. In the current project co-operator industrial practice, the CBN grinding segment stone changing period is decided based on the number of parts produced or the criteria such as occurrences of chatter, part surface deterioration or burn mark [4,5]. However, the imprecise method not only has lower efficiency but also could cause failure product and tool costs.

In order to maximize life utilization of the grinding tools, a digital twin system was developed for double size vertical grinding machine.

The virtual commission technology was implemented and connecting with the PLC program to describe the real-world operating conditions of the grinding machine. It integrates the spindle motor current data collected in the machining process for computation grinding force. The developed force prediction model will use to estimate the grinding tool changing period.

2. Conceptual framework
The conceptual framework of a digital twin for grinding machine consists of three parts, Physical space, virtual space and information processing and shown in figure 1. In the present work, the digital twin system can represent the real-time grinding process and grinding force prediction. The physical
space delivers the product pre-knowledge and sensor data to virtual space to build a virtual model of grinding machines. The virtual model of vertical double side grinding machine performing the machining process while connecting the PLC program. The sensor data will be collected in the local database. A predictive grinding force model will be built to anticipate the grinding wheel end of life and deliver the information to users through the platform interface.

![Figure 1. Digital twin framework for grinding machine.](image)

3. Implementation of digital twin for grinding machine

In the present work, a vertical double-disk grinding machine was used for the case study. In order to represent the real-time operational dynamics of its physical counterpart, a DT system of grinding process using the virtual commissioning technology was built, based on the physical production line factory. The grinding process conditions for build virtual model presented in table 1.

| Process information   | Operating conditions               |
|-----------------------|-----------------------------------|
| Machine type          | Vertical double-disk grinding (GRV-585) |
| Grinding Wheel        | CBN segment stone                 |
| Workpiece             | CN715 brake disk                  |
| Work spindle          | 250rpm                            |
| Upper wheel spindle   | 850rpm                            |
| Lower wheel spindle   | 850rpm                            |
| Work clamp            | 0.5~1.5Mpa                        |
| Feedrate              | 30μm/s                            |
| Spark out time        | 3 sec                             |

3.1. Modeling of the grinding machine

The virtual model refers to a digital representation of a physical system. The digital twin should mimic its physical counter part in geometry and functionality. The physical properties and motions to the CAD models which should similar to those of the actual physical system. The first step in the CAD
implementation was acquiring accurate dimensions of system and creating CAD models of the grinding machine components and shown in figure 2.

![Figure 2. Virtual model of grinding machine.](image-url)

The entire system was divided into several sub-assemblies. These included: the work piece, slide mechanism, motor, clamp assembly and control panel. Each of these sub-assemblies was drawn in virtual environment and later these sub-assemblies were put together to form the final assembly. To enable motion simulation, the physics, material and position control properties were configured into the CAD models and relevant joints assigned to connect the various components of the sub-assemblies and shown in figure 3.

![Figure 3. Modelling grinding machine.](image-url)

In order to realize real-time representation of the grinding process, the virtual commissioning technology was implemented. The motion control and logical control of the grinding process were analyzed in the Mitsubishi environment and PLC program was programmed in Siemens environment. Virtual model of the grinding machine was connected with virtual PLC controller by using commercial software and shown in figure 4.
To ensure flow of data and control signals between the physical system and the virtual model, a suitable means of communication is required. An interoperability standard for secure and reliable exchange of data in industrial automation is the Open Platform Communication (OPC). These standards are facilitated via Siemens SIMIT which provides client server communication. Through the server, information can be sent and stored from the digital twin to the physical system and vice versa.

The virtual grinding machine model was configured to communicate with server via the External Signal Configuration (ESC) feature. The ESC feature facilitated the merger between control signals from the digital twin to an external source. By using TIA portal connected to the server uses link tags that specify sensor and actuator control signals. These tags were then configured in the ESC feature, by assigning them addresses. This step completed the communication linkage between the digital twin and physical counterpart and shown in figure 5.

When the physical data is received, the system directly displays the data and records the data in the database for the historical data analysis and optimization. Finally, the geometric model of each device is updated in a 3D scene to realize the real-time 3D monitoring process.

3.2. Sensor signal acquisition and grinding force prediction
Electric drives and spindles provide the mechanical force necessary to remove material from the part. By the measurement of motor-related parameters such as motor power or current, both process power and, more recently, measures of the machine tool and drive condition can be realized. The major
advantage of motor-related parameters to detect malfunctions in the cutting process is that the measurement apparatus does not disturb the machining.

Motor current and power sensing use the motor itself as an indirect sensor of cutting force. Thus, when using sensor systems based on motor current or power, it is crucial that the relationship between input current/power and output force/torque is linear.

![Figure 6. Force chain in grinding machine.](image)

The Hall effect current HAL 100 sensor was mounted on the grinding machine. The sensor data will be collected in the local database. To reduce the redundant sensor data, similarity check under time and frequency domains will be performed. Grinding force estimated from the stored motor current data by eliminating inertial and frictional effects in the motor current and shown in the figure 6. The calculation method as in equation (1):

\[
T_m = J_\omega d\omega dt + T_{force} + T_f = K_r I_q
\]

Based on multi-domain analytics, the grinding force data will be analyzed for the diagnosis of significant malfunction occurrences during the grinding processes relative to energy and resource wastage. From the analyzed data, an effective grinding force feature signifying the segment grinding stone wear will be extracted. With the extracted feature, a predictive model will be built to anticipate the grinding wheel end of life.

4. Conclusions
In this paper, a real-time monitoring and control method through the use of a digital twin was proposed. The concept was implemented on a grinding machine system. First step in achieving this was the creation of 3D geometric model, physical model and kinematic model of the grinding machine. PLC program was programmed by analyse the grinding process and connect with the virtual model and linking model to its physical counterpart. A future step in this research is install motor current sensor in grinding machine to collect data. The data processing and prediction module will be developed.

5. References
[1] Lu, Y., Liu, C., Wang, K., Huang, H. and Xu, X. 2020 Digital Twin-driven smart manufacturing: Connotation, reference model, applications and research issues Robotics and Computer-Integrated Manufacturing 61, p.101837
[2] Zheng, Y., Yang, S. and Cheng, H. 2018 An application framework of digital twin and its case study Journal of Ambient Intelligence and Humanized Computing 10(3) 1141-1153
[3] Osinde, N., Byiringiro, J., Gichane, M. and Smajic, H. 2019 Process Modelling of Geothermal Drilling System Using Digital Twin for Real-Time Monitoring and Control Designs 3(3) p.45

[4] Kannan, K. and Arunachalam, N., 2018 A Digital Twin for Grinding Wheel: An Information Sharing Platform for Sustainable Grinding Process Journal of Manufacturing Science and Engineering 141(2) doi : 10.1115/1.4042076

[5] Teti, R., Jemielniak, K., O’Donnell, G. and Dornfeld, D. 2010 Advanced monitoring of machining operations CIRP Annals 59(2) 717-739

Acknowledgments
This work was supported by [20004615] (Building an Advanced Intelligent Smart Factory with IIoT and Big Data) Ministry of Trade, Industry & Energy (MOTIE).