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Design Considerations for Building an IoT Enabled Digital Twin Machine Tool Sub-System

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***Abstract*—The Internet of Things (IoT) and digital twins (DT) are both key advancements in the fourth industrial revolution. IoT can enable the connection of various devices which collect data that can be utilized to create a DT which can provide various services such as condition monitoring, predictive maintenance, modeling, and other useful functionality. Machine tools are key components in modern manufacturing forming the backbone of most modern factories. Modern machine tools are very complex and expensive machines, often costing hundreds of thousands to millions of dollars. It is desirable to ensure they are in good working condition. Given their complexity it may be desirable to begin IoT enabled DT development with one of its various sub-systems such as the feed drives, tool changer, or spindle. This work covers considerations when building an IoT-enabled sub-system DT including: which data streams can be utilized, what should be considered when selecting a DT platform, and how data will be transmitted and analyzed in the system. A case study of a linear feed drive IoT-enabled feed drive is examined under this framework of development. This work should aid others with beginning the development process for an IoT enabled DT sub-system of their own.**

***Index Terms*—digital twin, Internet of Things, machine tool, manufacturing**

I. Introduction

The manufacturing world has entered the fourth industrial revolution (4IR), often referred to as Industry 4.0. There are several key advancements in the 4IR including the implementation of the Internet of Things (IoT), artificial intelligence (AI), advanced condition monitoring (CM), and cyber-physical systems. One of the most interesting recent developments has been the concept of the digital twin (DT). DTs are virtual representations of physical objects, systems, processes, and places. They are connected to their physical counterpart via an array of sensors and feedback mechanisms. These sensors help to keep the DT updated to match the state of its physical twin. DTs can be used for a variety of purposes such as advanced control, simulation, and condition monitoring. Useful functionality provided by DTs is often referred to as DT services.

Condition monitoring is incredibly valuable in the manufacturing sector. Modern manufacturing relies on expensive capital investments in assets such as robots and machine tools. Computer numerical control (CNC) machine tools are the backbone of modern manufacturing. They are used to manufacture millions of high-precision components each year. These machines often cost hundreds of thousands, sometimes millions of dollars. Advanced CM techniques can lead to the implementation of predictive maintenance (PM). PM can help maximize the output of manufacturing equipment by increasing uptime, reliability, and asset performance.

DTs can be created for objects, systems, and systems of systems [1]. When beginning development of a DT system it may be worthwhile to start at a smaller scale and eventually build up the scale and complexity of the DT over time due to time and resource constraints. For this reason, it may be wise to begin with a subsystem, which is large enough in scale to be worthwhile, but small enough to be manageable. Machine tools consist of several important subsystems. These include the spindle, tool changer, cooling system, and feed drives to name a few. The focus of this paper will be the linear feed drive of a machine tool.

Linear feed drives are important in the function and performance of a machine tool. Part quality and machine reliability depend on the performance and reliability of the various feed drives. Linear feed drives consist of several important components: these include a ball screw, servo motor, linear guides, linear motors, couplers, and bearings [2]. Developing a DT for this subsystem can provide value through condition monitoring, predictive maintenance, simulation, and visualization capabilities.

There are many examples in the literature of leveraging DT or IoT technology to augment the capabilities of a machine tool. Tong et al. [3] created a DT framework for a machine tool for the purpose of data analysis, optimization and decision making, and data visualization. They applied their framework to a 5-axis machine tool and created a monitoring interface dashboard, they were able to optimize their tool path and improve surface finish. Wang et al. [4] created a DT-based method for multivariable dynamic modeling using in-process CNC data. They tested their method on a 5-axis laser drilling machine. Armendia et al. [5] evaluated the application of DTs to machine tools. They found that some of the key purported advantages of applying digital twins were the following: Increasing overall equipment efficiency, validating simulated results with actual results using sensors, reducing tool cost with improved tool selection, reducing scrap, and increasing up time. Qiao et al. [6] created a DT based condition monitoring method for machine tools. They predicted tool wear via a neural network using force and vibration data collected via a dynamometer and accelerometer respectively. After observing the literature it is clear that integrating both DT and IoT into a machine tool subsystem can provide a great deal of functionality for machine tools. DTs have been constructed for machine tools sub systems, most notably the spindle. They have been used to model and estimate the thermal characteristics of a spindle [7]. They have also been used to monitor the performance of a spindle via measuring and monitoring stiffness and vibration using both models and experimental results [8].

This work will cover the considerations when designing an IoT-enabled machine tool subsystem DT, using a feed drive as the case study. It is important to examine several criteria when building a subsystem. These criteria include which sensors and data sources should be used to collect data, which software package should be used to build the twin, and how data will be transmitted and processed.

The remainder of this work is organized as follows: section II will cover the selection of sensors and data streams for the system, section III will cover the options for DT development software, section IV will cover the data transmission and processing of the system, section V will display a case study, and finally section VI will conclude the work.

II. Data stream selection

The collection of data is required for the construction of a DT and its various services. There are four potential data streams that have been identified:

1) External sensors
2) Integrated sensors
3) Control signals
4) Production data

An overview of these data streams can be seen in Figure 1. Sensors can broadly be organized into two groups: integrated sensors and external sensors. Analysis methods using integrated sensors can be described as sensor-less and methods using external sensors can be described as sensor-based [9].

Integrated sensors are sensors that are installed in most CNC controllers and are necessary for their function. These include motor torque / current and rotary and / or linear encoder data such as position, velocity, and acceleration. Integrated sensors are advantageous as they do not incur any additional costs and there is no need to handle the complexity of sensor mounting, data collection, and data processing. A great deal of analysis can be performed with just integrated sensors. One example of analysis using integrated sensors would be to measure backlash using the difference between the rotary and linear encoder [10].

External sensors are sensors not necessary to the function of the machine, but may provide useful data. Common external sensors include: force sensors, accelerometers, and temperature sensors [11]. These sensors are used for a variety of analyses that cannot be performed using just integrated sensors. Many methods in the literature utilize vibration analysis techniques which require accelerometers or other vibration measuring sensors to collect data. For example, vibration data can be used to estimate the remaining useful life in ball screws [12]. When using external sensors it is important to properly manage cables to avoid damaging components. It is recommended to have some sort of cable track to protect all sensor cables. It may also be necessary to use a data acquisition (DAQ) device to collect data from external sensors.

In addition to sensors, data can be obtained via from the control system. This data can include measurements such as torque set point, position set point, and velocity set point. This data is especially useful to compare against actual values, such as comparing actual motor torque versus motor torque set point. For example, in-process CNC data can be used to estimate multivariable dynamics models, as was done in a study by Wang et al. [13].

Data from production can be used as well. Data such as the number of cuts performed by a specific tool, the number of defects or rejects for a specific part, measured surface roughness, or the process time for each operation can be used. A few examples of this would be utilizing the number of cuts a tool has performed to make a prediction of its level of wear, or utilizing the number of rejected components as a measure of the positioning accuracy and rigidity of the feed drives. One example by Vishnu et al. [14] was building a DT process for predicting surface roughness and comparing it to actual surface roughness data collected from measurements.

Many forms of analysis will use one or more of these possible data streams. Often utilizing multiple data streams can enable more accurate estimates of conditions, control performance, and improved modeling. Sensor fusion is often utilized to make more accurate estimates of parameters than a single set of sensors would be. Yang et al. [15] and Luo et al. [16] improved their degradation and Remaining useful life models respectively using a particle filter and found that it had substantially smaller prediction error than both the data and model-based methods. In addition to using sensor fusion just on multiple sensors, it can be applied across the possible data streams. Vibration and force data could be used to build a wear estimation algorithm, this can be compared to production data about the amount and types of cuts being performed with a given tool. The estimations of these can be fused and compared

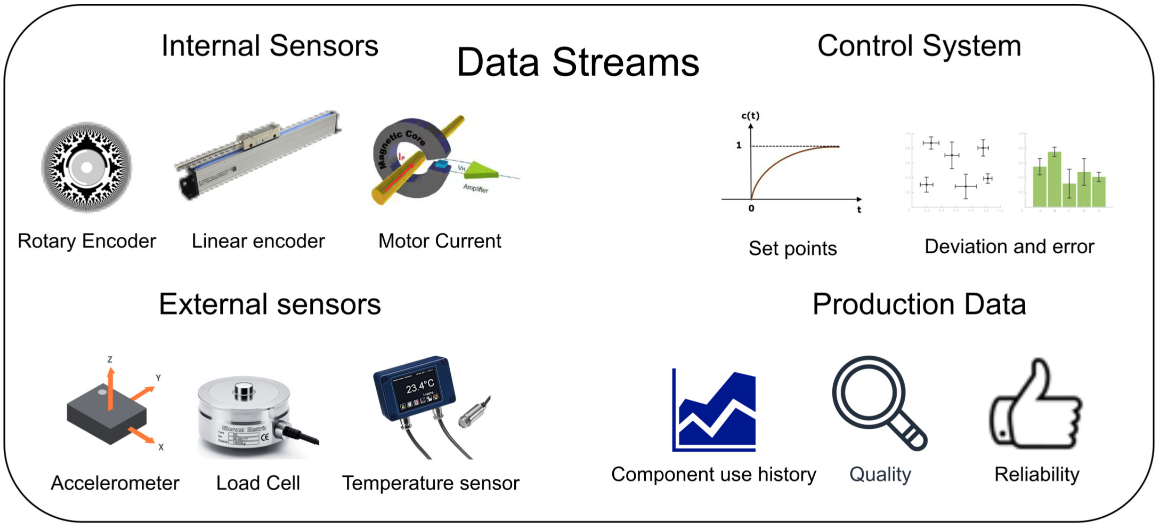

Fig. 1. Data streams in an IoT DT subsystem

to data about the wear and useful lifetime of cutting tools to validate the estimation algorithms.

III. Digital Twin Platforms

There are several considerations when selecting a platform to build a DT for the machine tool subsystem. One of the first considerations is the compatibility with the various software systems involved. These include the machine tool CNC control software, other manufacturing and design software systems including the computer-aided design, engineering, and manufacturing software (CAD, CAE, CAM), as well as the enterprise resource planning (ERP) software. Easy compatibility ensures easier transfer and sharing of data as well as ease of development. Ideally software packages will have various capabilities that are useful in a digital twin system such as simulation, data analysis, data visualization, and multi domain modeling to name a few.

Another consideration is the cost of the platform. Some software used to construct DTs is open source, others are offered as paid add-ons to their CAD/CAM/CAE software, some are offered as a service (SaS) and others are stand-alone packages. Thought needs to be put into which offering makes the most economic sense for the users' given situation. The relative benefit of implementing a DT needs to exceed the costs of licensing the software, and developing and maintaining the DT.

Many CNC software developers have recently begun developing and releasing DT software. FANUC offers two programs in their catalogue, CNC GUIDE 2 and Servo Viewer, to accurately simulate and optimize machining processes. SINUMERIK ONE is the CNC platform offered by Siemens which is built with the intention of developing a DT. In addition to the CNC control system, it is important to evaluate what DT building software is available. Many of the large CAD software developers offer a DT building software or platform. Ansys software offers a DT building software called "Ansys digital twin". Dassault and Autodesk developers of Solidworks and AutoCAD / Inventor respectively both offer DT platforms. Dassault offers the 3DEXPERIENCE and Autodesk offers the Autodesk platform services (formerly Forge) and Tandem for the architectural engineering and construction (AEC) industry. Large tech software companies such as Amazon and Microsoft have begun offering IoT and DT-based software. Amazon offers AWS IoT and Microsoft offers Azure IoT. Siemens also offers DT solutions through its NX platform. The Mechatronic concept designer (MCD) add-on as well as the PLCSIM software can be used to build DTs of manufacturing systems.

IV. Data transmission and analysis

An important consideration when designing an IoT or DT system is what data will be collected and where it will be stored and processed. It is important to consider the network topology of the system based on the most effective line of communication. Various shapes of networks exist such as ring, bus, line, ring, mesh, star, and tree, and fully connected. It is also possible to have a hybrid of one or more network shapes. For a machine tool subsystem, a tree shape likely makes the most sense. A subsystem needs to receive information from its various sensors, and it needs to receive and transmit data to the IO and control system of the CNC control system. A simple diagram with an overview of the data connections can be seen in Figure 3.

Additionally, it is worth considering the nature of the connection and the requirements for throughput, reliability, mobility, and extendibility. Different types of wired or wireless connections can be considered such as ethernet, wifi, Bluetooth, or 5G. Given the static nature of a subsystem, a wired connection is most often going to be the reasonable choice both for the sensors and for connecting to the CNC control system.

It is also worth considering where the data analysis and storage will occur. A few considerations need to be made when

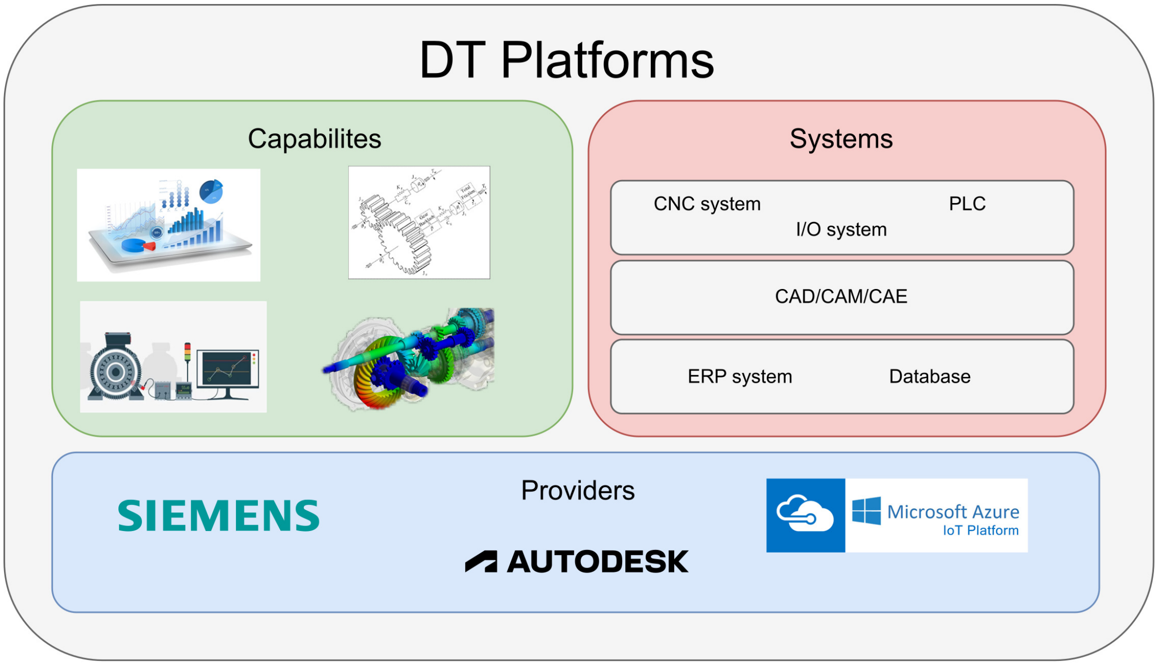

Fig. 2. Requirements for digital twin platforms in an IoT application

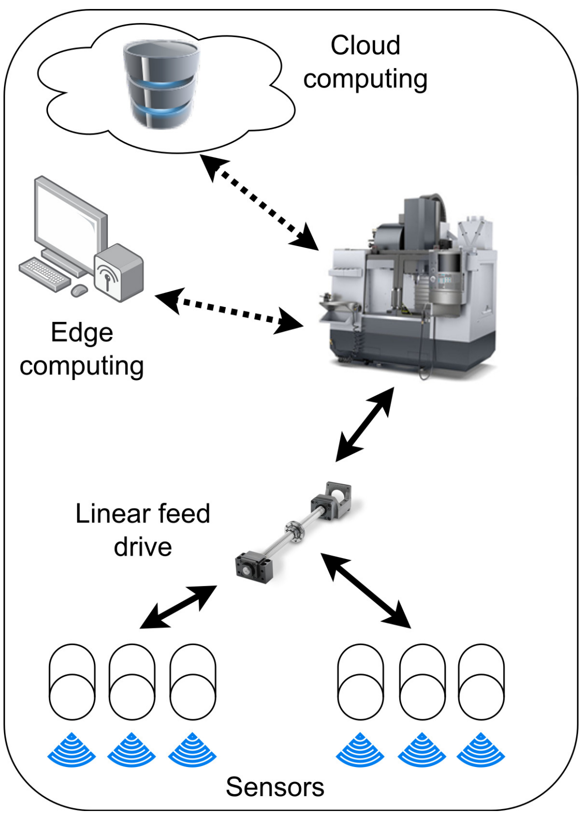

Fig. 3. Data transmission and analysis in a digital twin system

making this decision. How much data is needed to be stored and for how long, the required speed of the analysis and data transmission, and the complexity and scale of the analysis to be performed. Several types of data will be generated and utilized in a machine tool feed drive DT. High-frequency transient data will be generated via the various sensors such as the accelerometer and encoders. This data will often be collected at a frequency ranging from 1-100 kHz and often will be discarded soon after it is used in the control system or after features are extracted. Historical data and features will be collected and generated by the system. This data will be at a lower frequency than the raw sensor data but will still likely be in the 100 Hz to 10 kHz range. One example of this type of data would be the maximum amplitude of vibration sampled at various time periods from one of the accelerometers. This data will need to be stored for analysis and historical trend analysis.

V. Case Study

The example case study presented in Figure 4 is a machine tool feed drive DT test bench, which is currently being developed. The purpose of this experimental setup is to develop a DT for a machine tool feed drive which will be used for condition monitoring and predictive maintenance. Implementing predictive maintenance will improve the reliability of the subsystem which will in turn improve produced part quality and manufacturing throughput. The system was constructed using Siemens control and motion equipment and utilizes the Siemens software package.

The system utilizes various data streams. It utilizes various external sensors such as accelerometers and load cells to measure vibrations and forces respectively. Integral sensors such as linear, and rotary encoders will be used. Control signals such as torque set point, and position set point are utilized and can be used for estimates of system parameters

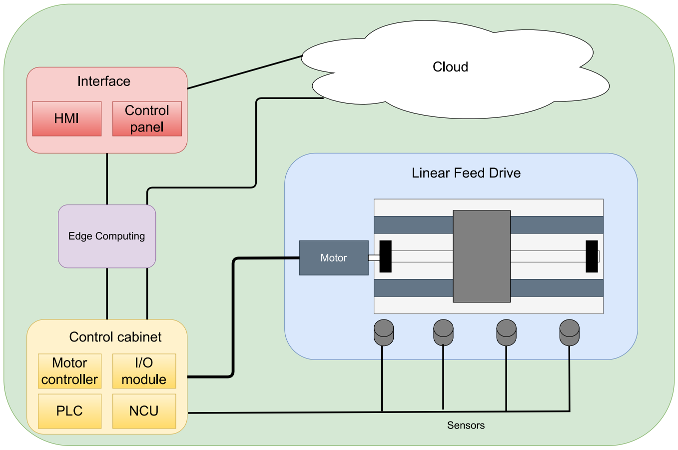

Fig. 4. Case study of a linear feed drive DT

such as stiffness, inertia, and friction. Component life data such as the number of cycles ran will be used when evaluating the wear characteristics of the system. These various data streams can be used to perform various types of analysis such as machine learning, and estimation using various filtering methods like the Kalman filter. The Siemens NCU system includes a modular IO system which can be expanded with various digital and analogue input and output data streams.

The system utilizes Siemens CNC and DT and IoT software. The control system is the Siemens Sinumerik ONE CNC system using the Siemens 1750 NCU. Both SINUMERIK edge computing and the Mindsphere IoT platform are utilized for collecting and analyzing data. The DT for this system is constructed using the Siemens NX platform mechatronic concept designer, which allows the construction and simulation of a virtual representation of the system.

VI. Conclusion

This work investigates considerations when building a DT sub-system of a machine tool. Three important considerations that were discussed were the data streams that can be utilized, what platform or software will be used to build the DT, and how data will be transmitted and analyzed. A case study of a linear feed drive DT which is currently being developed is used to illustrate the system. This work can help others who wish to develop a machine tool sub-system DT. This work focused on linear feed drives but the principles can be applied to other sub-systems such as spindles, tool changers, rotary feed drives, or cooling systems.

Currently work on constructing this case study system is underway. Once completed future work can involve discussing the advantage provided by the various services that the linear feed drive DT can provide. These services include condition monitoring, predictive maintenance, and system modeling.

References

[1] F. Tao, W. Liu, M. Zhang, T. Hu, Q. Qi, H. Zhang, F. Sui, T. Wang, H. Xu, Z. Huang, X. Ma, L. Zhang, J. Cheng, N. Yao, W. Yi, K. Zhu, X. Zhang, F. Meng, X. Jin, and Y. Luo, "Five-dimension digital twin model and its ten applications," *Jisuanji Jicheng Zhizao Xitong/Computer Integrated Manufacturing Systems, CIMS*, vol. 25, pp. 1–18, Jan. 2019.

[2] Y. Altintas, A. Verl, C. Brecher, L. Uriarte, and G. Pritschow, "Machine tool feed drives," *CIRP Annals*, vol. 60, no. 2, pp. 779–796, Jan. 2011.

[3] X. Tong, Q. Liu, S. Pi, and Y. Xiao, "Real-time machining data application and service based on IMT digital twin," *Journal of Intelligent Manufacturing*, vol. 31, no. 5, pp. 1113–1132, Jun. 2020.

[4] C.-P. Wang, K. Erkorkmaz, J. McPhee, and S. Engin, "In-process digital twin estimation for high-performance machine tools with coupled multibody dynamics," *CIRP Annals*, vol. 69, no. 1, pp. 321–324, Jan. 2020.

[5] M. Armendia, F. Cugnon, L. Berglind, E. Ozturk, G. Gil, and J. Selmi, "Evaluation of Machine Tool Digital Twin for machining operations in industrial environment," *Procedia CIRP*, vol. 82, pp. 231–236, Jan. 2019.

[6] Q. Qiao, J. Wang, L. Ye, and R. X. Gao, "Digital Twin for Machining Tool Condition Prediction," *Procedia CIRP*, vol. 81, pp. 1388–1393, Jan. 2019.

[7] J. Xiao and K. Fan, "Research on the digital twin for thermal characteristics of motorized spindle," *The International Journal of Advanced Manufacturing Technology*, vol. 119, no. 7, pp. 5107–5118, Apr. 2022.

[8] R. Xue, X. Zhou, Z. Huang, F. Zhang, F. Tao, and J. Wang, "Digital twin-driven CNC spindle performance assessment," *The International Journal of Advanced Manufacturing Technology*, vol. 119, no. 3, pp. 1821–1833, Mar. 2022.

[9] Q. Butler, Y. Ziada, D. Stephenson, and S. Andrew Gadsden, "Condition Monitoring of Machine Tool Feed Drives: A Review," *Journal of Manufacturing Science and Engineering*, vol. 144, no. 100802, Jun. 2022.

[10] P. Chandrasekar and K. Srinivasan, "Inferential based measurement of backlash in servo system," *Materials Today: Proceedings*, vol. 46, pp. 9766–9770, Jan. 2021.

[11] B. Sicard, N. Alsadi, P. Spachos, Y. Ziada, and S. A. Gadsden, "Predictive Maintenance and Condition Monitoring in Machine Tools: An IoT Approach," in *2022 IEEE International IOT, Electronics and Mechatronics Conference (IEMTRONICS)*, Jun. 2022, pp. 1–9.

[12] J. Wen and H. Gao, "Remaining useful life prediction of the ball screw system based on weighted Mahalanobis distance and an exponential model," *Journal of Vibroengineering*, vol. 20, no. 4, pp. 1691–1707, 2018.

[13] C.-P. Wang, K. Erkorkmaz, J. McPhee, and S. Engin, "In-process digital twin estimation for high-performance machine tools with coupled multibody dynamics," *CIRP Annals*, vol. 69, no. 1, pp. 321–324, Jan. 2020.

[14] V. S. Vishnu, K. G. Varghese, and B. Gurumoorthy, "A Data-driven Digital Twin of CNC Machining Processes for Predicting Surface Roughness," *Procedia CIRP*, vol. 104, pp. 1065–1070, Jan. 2021.

[15] X. Yang, Y. Ran, G. Zhang, H. Wang, Z. Mu, and S. Zhi, "A digital twin-driven hybrid approach for the prediction of performance degradation in transmission unit of CNC machine tool," *Robotics and Computer-Integrated Manufacturing*, vol. 73, p. 102230, Feb. 2022.

[16] W. Luo, T. Hu, Y. Ye, C. Zhang, and Y. Wei, "A hybrid predictive maintenance approach for CNC machine tool driven by Digital Twin," *Robotics and Computer-Integrated Manufacturing*, vol. 65, p. 101974, Oct. 2020.