

# Five-Dimensional Modeling Technology for Intelligent Manufacturing Lines Oriented Towards Digital Twins

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## ABSTRACT

Intelligent manufacturing lines constitute a complex system characterized by the integration of multiple technologies, the intersection of various disciplines, multi-dimensional integration, and the interaction of numerous components. Currently, the internal environment of intelligent manufacturing workshops, processing technologies, and production processes all exhibit a high degree of complexity, and the diversity of underlying mechanical equipment is particularly notable. Compared to traditional manufacturing assembly lines, the process coupling between equipment in flow-type production lines is tighter and more significant. Therefore, this paper undertakes digital twin modeling of intelligent manufacturing lines from five aspects: geometry, motion, data, communication, and control. This approach aims to achieve precise and detailed mapping of the physical entity production line's processing operations.

## KEYWORDS

Digital Twin; Intelligent Manufacturing; Modeling Technique.

## 1. INTRODUCTION

In 2002, Professor Michael Grieves [1, 2] of the University of Michigan first introduced the concept of 'creating digital twin mirrors for physical entity objects', a notion that was later named digital twin technology. This idea has been further supplemented and elaborated by numerous scholars in the industrial and smart manufacturing sectors. Currently, NASA's [3] definition of digital twin technology has garnered extensive support and widespread recognition from scholars and manufacturers alike. This definition posits that a digital twin maximizes the use of simulation models, sensor updates, operational logs, and other data, integrating multi-disciplinary, multi-perspective, multi-physical quantity, and multi-probability simulation processes. Thus, it reflects the entire lifecycle of the corresponding physical equipment in the information space [4].

## 2. DIGITAL TWIN MODEL REQUIREMENTS ANALYSIS

As a physical entity, the intelligent manufacturing line serves as the foundation for the entire data collection and remote monitoring system. Building a three-dimensional virtual model of the production line within the twin platform maps the actual intelligent manufacturing line's processing operations. Moreover, the equipment model needs to accurately and clearly display the actions of the underlying equipment during actual processing and production. After a detailed analysis of the processing technology sequence of the intelligent manufacturing line and the manufacturing action flow of the underlying equipment, the intelligent manufacturing line has the following requirement characteristics:

(1) When constructing the virtual model in the digital twin platform, the model needs to precisely reflect the physical entity of the intelligent manufacturing line. Digital twin technology is established on top of the physical workshop, achieving the projection of the physical production line in a three-dimensional virtual environment. To ensure the accuracy of the three-dimensional digital twin model, it is essential to establish accurate models of the underlying mechanical equipment. These models should realistically reproduce the action details and behavior processes of the mechanical equipment during the processing. In the construction process of the three-dimensional model, it is necessary to comprehensively consider the shape, size, and movement range thresholds of the physical mechanical equipment to ensure the feasibility and rationality of the model. At the same time, the virtual model should be optimized for lightweight processing to enable smoother mapping of the intelligent manufacturing line's processing actions within the digital twin platform [5].

(2) The physical workshop and its twin should be capable of real-time communication with external control devices, that is, achieving real-time communication with data collection systems and remote monitoring systems.

### 3. LITERATURE REFERENCES

Five-dimensional modeling technology primarily models the digital twin of intelligent manufacturing lines from five aspects: geometry, motion, data, communication, and control. During modeling, the characteristics of each aspect are distilled into mathematical models, hereby defining a multivariate mathematical model [6]:

$$DT = \{GM, MM, DM, ComM, ConM\} \quad (1)$$

The elements in equation (1) respectively represent: geometric aspect model, motion aspect model, data aspect model, communication aspect model, control aspect model. Among them:

$$GM = \{G\_Point, G\_Line, G\_Surface, G\_Body, G\_Coo\} \quad (2)$$

The elements in equation (2) represent: points, lines, surfaces, volumes, coordinates, used for describing the motion relationship of the digital twin model within the digital twin environment and for model presentation.

$$MM = \{C\_Vel, C\_Vela, C\_W, C\_Wa\} \quad (3)$$

The elements in equation (3) are respectively: velocity, acceleration, angular velocity, angular acceleration, used to describe the motion of the digital twin equipment model.

$$DM = \{DRM, SGM, PD\} \quad (4)$$

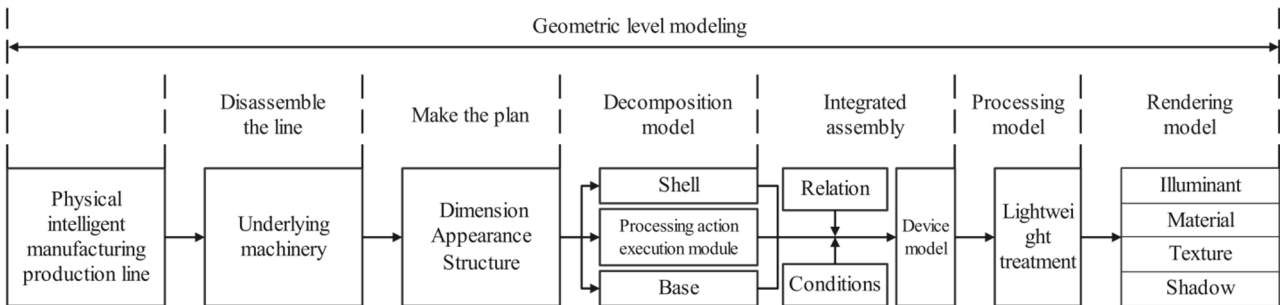
The elements in equation (4) represent: data relationship model, static geometric model of the intelligent manufacturing line, production data, used for the integrated modeling of mechanical equipment twin model with production data.

#### 3.1. Geometric Level Modeling

Within the physical entity of an intelligent manufacturing line, there are various types of manufacturing equipment including CNC machine tools, six-axis industrial robots, and automated storage and retrieval systems. Before constructing the digital twin of the intelligent manufacturing line on the twin platform using digital twin technology, the production line is first disassembled, and the underlying mechanical equipment that has been dismantled is analyzed and modeled on a geometric level.

The process of geometric level modeling is illustrated in Figure 1:

- (1) Disassemble the production line: Disassemble the intelligent manufacturing line of the physical entity, and analyze and model each piece of underlying mechanical equipment within the line separately;
- (2) Develop a plan: Formulate a plan for building the model. Measure the physical entity's underlying mechanical equipment, and determine the equipment model's shape, structure, and specific dimensions based on the measurements and the equipment's factory specifications, thereby establishing a construction plan for the mechanical equipment model.
- (3) Decompose the model: The mechanical equipment model consists of many devices and parts. Therefore, when modeling the actual equipment, it is necessary to decompose the equipment into parts that can be independently designed in three-dimensional modeling software, and then draw each decomposed part model.
- (4) Integrate assembly: After all the decomposed parts have been drawn, integrate and assemble the part models according to assembly parent-child relationships and constraint conditions to form the underlying mechanical equipment in the complete intelligent manufacturing line.
- (5) Process the model: After the mechanical equipment model has been drawn, perform lightweight processing on the model;
- (6) Render the model: Using 3D modeling rendering software, render the initial model of the equipment from multiple perspectives such as light sources, materials, textures, shadows, shaders, etc., to enhance the model's realism and aesthetics.

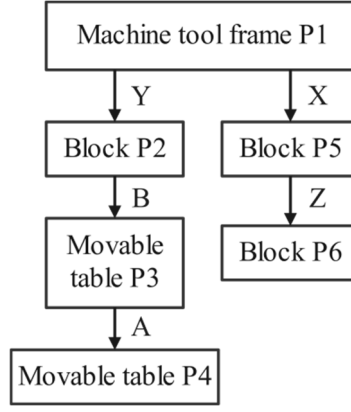


**Figure 1.** Geometric level modeling process

### 3.2. Motion Level Definition

The digital twin model of the intelligent manufacturing line can map the processing operation of the physical production line completely, so it is necessary to define the already constructed mechanical equipment model on the motion level. When the digital twin equipment model is in motion, it must follow the objective laws of reality. To prevent issues such as initial pose errors, boundary condition errors, imprecise contact collisions, and incorrect machining workpiece attributes when the mechanical equipment model maps the operation of the physical production line, it is essential to define attributes such as the starting position, ending position, activity range threshold of the action execution module, and friction collision constraint conditions on the motion level.

This paper takes the five-axis machining center in the intelligent manufacturing line as an example to introduce how to define the digital twin model from the motion level. The five-axis machining center is a complex multi-body system composed of rigid and flexible parts. The components of the five-axis machining center work together through the constraints at the motion level, forming a machining device with five degrees of freedom. The structure of this machining center can be viewed as a topological network consisting of six main nodes, as shown in Figure 2.



**Figure 2.** Topology of five-axis machining center

### 3.3. Data Level Integration

To achieve the projection and mapping of the digital twin model onto the physical intelligent manufacturing line, by constructing an integration method and relationship between the twin model and production data, a process-oriented digital twin model of the intelligent manufacturing line is formed. The mathematical description is as follows [7]:

$$F = O \cup U \quad (5)$$

$$DDRM = \{S, C\} \ \& \ S \Rightarrow C \quad (6)$$

$$O = \{o_1, o_2, \dots, o_q\} \quad (7)$$

$$C = \{c_1, c_2, \dots, c_i\} \ \& \ \sum_{i=1}^i c_i \Rightarrow WE \Rightarrow Z \quad (8)$$

$$S = \{s_1, s_2, \dots, s_p\} \ \triangleleft \triangleright \ U = \{u_1, u_2, \dots, u_p\} \quad (9)$$

$$Z \Leftrightarrow F \quad (10)$$

Where: F defines a rational evaluation criterion; O defines rational constraint relationships; U defines reasonable operational thresholds; S defines the equipment operation data set; C defines the production process data set including process parameters; WE defines workshop events; Z defines the event evaluation mechanism; defines the matching of equipment operation data with operational threshold characteristics;  $\Leftrightarrow$  defines the effective integration of rational evaluation criteria and event evaluation mechanisms.

### 3.4. Communication Level Development

After Geometric level modeling, motion level definition, and data level integration of all the underlying mechanical equipment in the intelligent manufacturing line, it is necessary to achieve interconnectivity between the digital twin model and the physical entity equipment. That is, to develop the communication interface between the digital twin model and the physical entity equipment at the communication level. The development of the communication interface includes two aspects: on one hand, using Python scripts within the digital twin simulation software to write communication interfaces for each piece of underlying equipment model; on the other hand, using the C# programming language on the supervisory computer of the intelligent manufacturing line to write exclusive model action drivers for each piece of underlying equipment. The process of communication level development is shown in Figure 3.

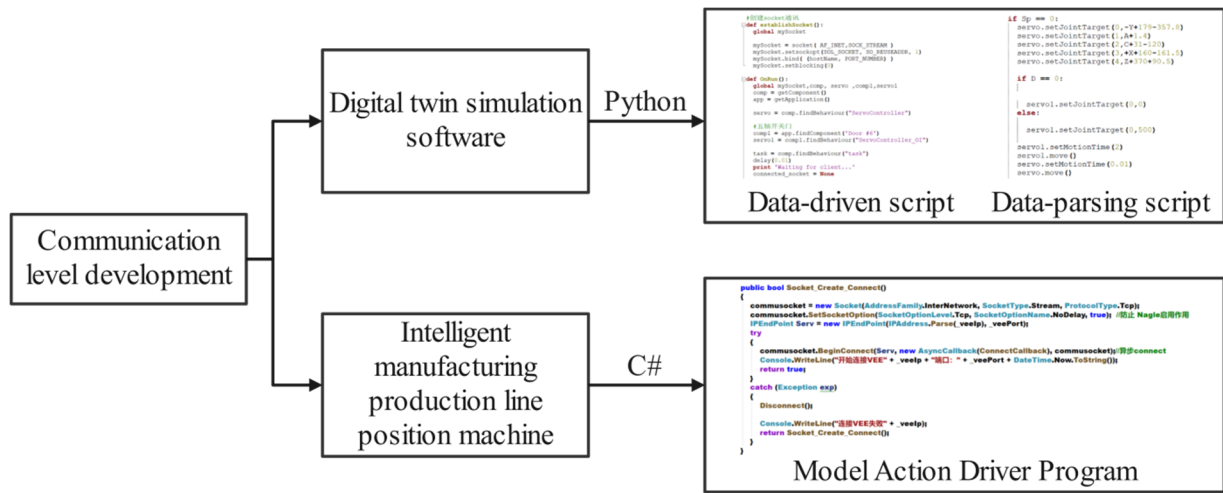


Figure 3. Communication level development process

### 3.5. Control Level Programming

After Geometric level modeling, motion level definition, data level integration, and communication level development for individual underlying mechanical equipment within the intelligent manufacturing line, it is necessary to control the overall machining operations and production process of the line. This means implementing programming at the control level for the digital twin model of the intelligent manufacturing line.

Control level programming refers to controlling the digital twin model of the intelligent manufacturing line by writing PLC (Programmable Logic Controller) control programs within a physical PLC or PLC software programming tool. This simulates the machining operation process of the physical production line. Based on the actual start-stop sequence of the underlying mechanical equipment in the production line and the machining operations, the production line model within the digital twin virtual environment is defined in terms of operations.

## 4. SUMMARY

This paper focuses on constructing a three-dimensional digital twin environment model for the workshop of a physical entity intelligent manufacturing line. It explores the concept of digital twin technology in the field of intelligent manufacturing and proposes a five-dimensional modeling technique. For the physical production line, modeling is conducted from a geometric perspective, completing a static description of the underlying mechanical equipment models. By defining at the motion level, integrating at the data level, developing at the communication level, and programming at the control level, the dynamic replication of the production line's machining operation process is achieved, establishing the digital twin model of the intelligent manufacturing line.

## CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

## REFERENCES

[1] GRIEVES, M., VICKERS, J. (2017) Digital twin: mitigating unpredictable, undesirable emergent behavior in complex system. Trans-disciplinary Perspectives on Complex Systems. Berlin, Germany: Springer-Verlag, [https://doi.org/10.1007/978-3-319-38756-7\\_4](https://doi.org/10.1007/978-3-319-38756-7_4).

- [2] Grieves, M. (2011) Product Lifecycle Management: Driving the Next Generation of Lean Thinking. *Journal of Product Innovation Management*, 24(3):278-280.
- [3] GLAESSGEN, E., STARGEL, D. (2012) The Digital Twin Paradigm for Future NASA and U.S. Air Force Vehicles. *Aiaa/ asme/asce/ahs/asc Structures, Structural Dynamics & Materials Conference Aiaa/ asme/ahs Adaptive Structures Conference Aiaa*. <https://doi.org/10.2514/6.2012-1818>.
- [4] Yu, Y., Fan, S, Y., Peng, G, W. (2017) Discussion on the application of digital twin model in product configuration management. *Aeronautical Manufacturing Technology*, 526(7):41-45. <https://doi.org/10.16080/j.issn1671-833x.2017.07.041>.
- [5] Gao, Y, J. (2021) Research on digital twin simulation technology of production line. *Nanjing University of Science and Technology*. <https://doi.org/10.27241/d.cnki.gnjgu.2021.001607>.
- [6] Ke, Z, S. (2022) Design of intelligent virtual production line and debugging system for digital twin. *Tianjin University Of Technology And Education*. <https://doi.org/10.27711/d.cnki.gtjgc.2022.000040>.
- [7] Yin, Y, C., Li, W., Tang, J. (2023) Research and development of digital twin system in process manufacturing workshop driven by data-model fusion. *Computer Integrated Manufacturing Systems*,29(06):1916-1929. <https://doi.org/10.13196/j.cims.2023.06.011>.