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Development of a Cloud Platform for Laser Cladding Based on Digital Twin

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ABSTRACT

To address the issues in traditional laser cladding systems—such as reliance on manual experience for process parameters, severe data silos, and the lack of real-time monitoring and closed-loop control—this study develops an intelligent manufacturing cloud platform system based on Digital Twin (DT) technology. Firstly, a parametric virtual simulation environment is established by developing custom process components within the Siemens Plant Simulation DT platform. Secondly, real-time data interaction between Plant Simulation and the underlying PLC is achieved via the OPC UA protocol, enabling millisecond-level data acquisition from physical equipment and synchronization with the virtual model. Finally, the self-developed Industrial Internet cloud platform is integrated using the MQTT protocol, resulting in a cloud system comprising three core modules: equipment management, real-time monitoring, and historical data traceability. This research realizes full-process data integration and real-time interaction among physical equipment, the digital twin, and the cloud platform. The developed cloud platform enables remote, real-time status monitoring and visualization of the laser cladding process, thereby providing critical technical support for intelligent process optimization and cross-regional collaborative management.

KEYWORDS

Laser Cladding; Digital Twin; Cloud Control System; Virtual Simulation; Cloud Platform.

1. INTRODUCTION

Laser cladding is an advanced surface modification technology that utilizes a high-energy laser beam to melt materials and form high-performance coatings on substrates. It enhances the wear resistance, corrosion resistance, and heat resistance of components, enabling the repair and remanufacturing of damaged parts.

Traditional systems face three major challenges that restrict their large-scale application and process consistency: severe data silos, unstable parameter calibration relying on manual experience, and the lack of real-time monitoring and closed-loop control. The Industrial Internet cloud platform addresses these issues by achieving seamless integration of full-process production data through the precise mapping and real-time interaction between physical entities and their digital twins.

This study develops an intelligent manufacturing cloud control system for laser cladding based on Digital Twin (DT) technology. Siemens Plant Simulation is employed to construct a parametric virtual simulation environment. The OPC UA protocol ensures millisecond-level data interaction between the simulation and the underlying PLC, while the MQTT protocol connects the system to a self-developed Industrial Internet cloud platform. The cloud platform features three core modules: equipment management, real-time monitoring, and historical data traceability.

The system realizes full-process data integration and interaction among physical equipment, the digital twin, and the cloud platform. It possesses functions including remote visual monitoring, intelligent parameter regulation, and cross-regional collaborative management, thereby providing critical technical support for the intelligent transformation of manufacturing and green remanufacturing.

1.1. Research on the Integration of Digital Twin and Cloud Platform Technology

Digital Twin technology provides physical entity mapping and simulation prediction capabilities, thereby expanding specific application scenarios for cloud services and effectively addressing the disconnection between computing resources and practical application requirements. Conversely, cloud services overcome the scene limitations and barriers to large-scale promotion associated with local deployment of Digital Twin technology by offering fundamental support such as data storage, computing scheduling, and service extension. The deep integration of these two technologies is essentially about the synergistic optimization of Digital Twin's modeling and analytics capabilities with cloud services' storage and distribution capabilities. This convergence drives the evolution of industrial intelligence from traditional standalone automation toward cloud-based collaboration and full-process intelligence, offering industrial fields—such as laser cladding—technical solutions that are low-cost, high-precision, and scalable. [1]

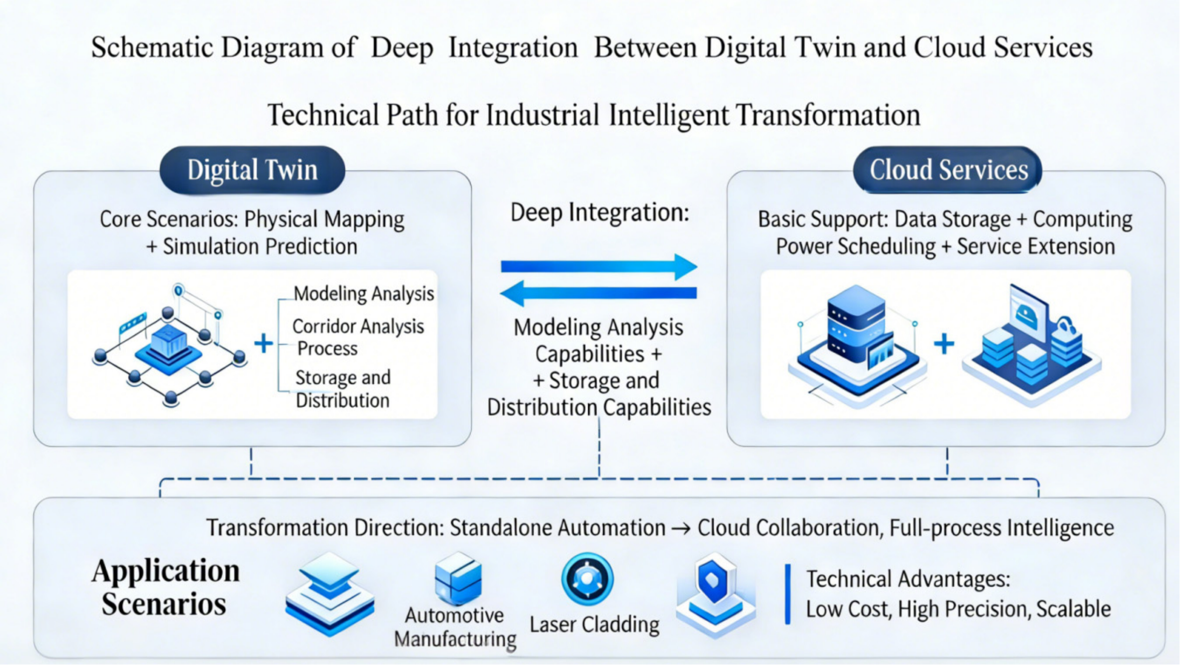

Figure 1. Integration of Digital Twin and Cloud Services

1.2. Overview of Industrial Internet Cloud Platform Technology

As a key carrier of digital twin systems, the industrial internet cloud platform achieves collaborative optimization between physical devices and virtual models through three core capabilities: data integration, edge computing, and application development. Its technical architecture can be divided into three layers: the perception layer, the platform layer, and the application layer.As shown in Fig2. The perception layer collects real-time device data via protocols such as OPC UA and Modbus TCP; the platform layer provides data storage (e.g., time-series databases), modeling and analysis (digital twin engines), and API services; the application layer develops functional modules for specific scenarios. Its development can be traced back to 2012, when General Electric (GE) in the United

States released the white paper "Industrial Internet: Breaking the Boundaries of Intelligence and Machines," first proposing the concept of the industrial internet and emphasizing the optimization of industrial efficiency through machine interconnection and data analysis [2]. From 2015 to 2017, it entered the technical exploration phase, during which the Industrial Internet Industry Alliance published the "Industrial Internet Platform White Paper," clarifying the platforms technical architecture and core capabilities, and promoting the standardization of device cloud migration and data integration [3]. After 2018, it entered the large-scale application phase. According to the "Cloud Computing Development White Paper" by the China Academy of Information and Communications Technology, the global industrial cloud platform market has a compound annual growth rate exceeding 35%, forming a three-tier technical system of "edge computing-cloud platform-industrial APP" [4].

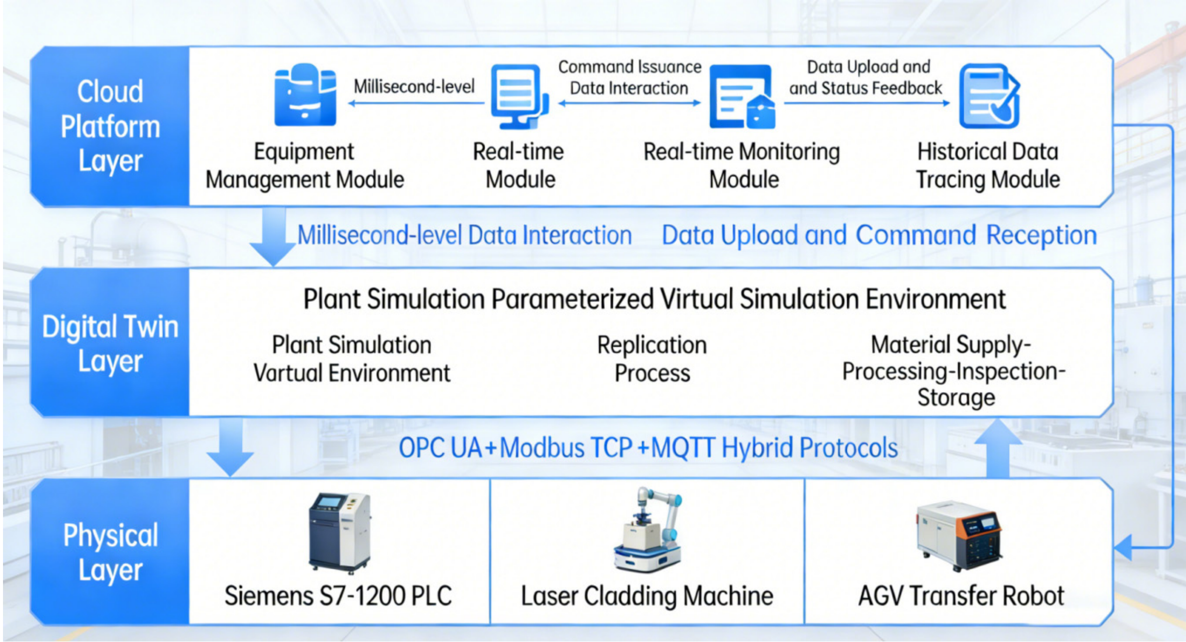

Figure 2. Technical Solution of Laser Cladding Cloud Platform Based on Digital Twin

2. ESTABLISHMENT OF THE DIGITAL TWIN FOR THE LASER CLADDING CLOUD SYSTEM

This study constructs the digital twin of the laser cladding system using Plant Simulation software. The architecture, illustrated in Figure 3, centers on the laser cladding process as the core production phase. It follows the intelligent manufacturing workflow of "material supply – processing production – quality inspection – finished product storage," ensuring the orderly arrangement of functional units.

The material supply module, located in the bottom-left corner of the system, serves as the material input port and consists of standardized loading stations and material positioning units. The transportation module runs throughout the entire layout, utilizing AGV precise positioning nodes (marked by red circles) as the core. Combined with multi-segment conveyors and diversion transfer structures, it establishes a material flow hub connecting all modules.

At the center of the layout lies the core production module: the laser cladding processing unit, which performs the laser cladding forming task on the substrate. The output end of this unit connects to the quality inspection module, deployed at the diversion node of the transportation module, for online quality screening of the processed parts. The final stage of the system is the multi-level zoned storage module, divided into storage areas for qualified finished products and materials awaiting rework, serving as the material output and temporary storage terminal.

The overall layout achieves seamless integration of all modules through the transportation system, forming a closed-loop production process. This design not only meets the high-precision process requirements of laser cladding but also accommodates the system's characteristics of flexible production and intelligent management. Figures 4 and 5 show the material supply unit and the laser cladding production unit, respectively, simulated and constructed on the cloud platform.

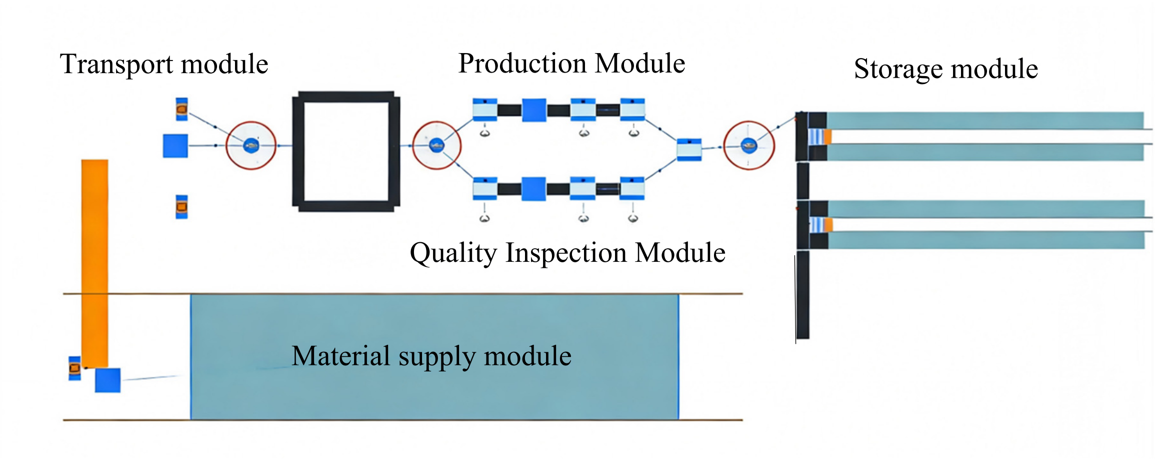

Figure 3. 3D Model of Hardware Layout for Laser Cladding Cloud System

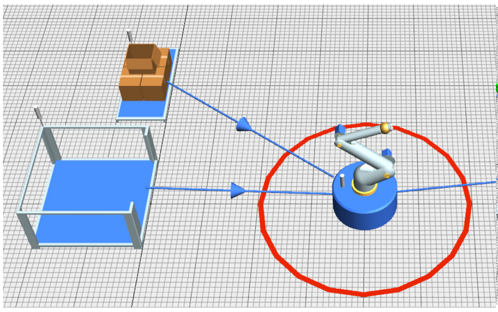

Figure 4. Logistics Supply Module

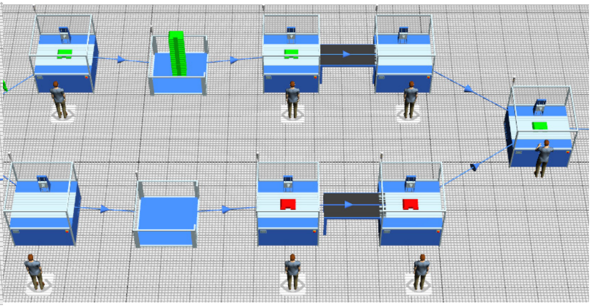

Figure 5. Production Module

3. COMMUNICATION PROCESS OF THE LASER CLADDING CLOUD SYSTEM

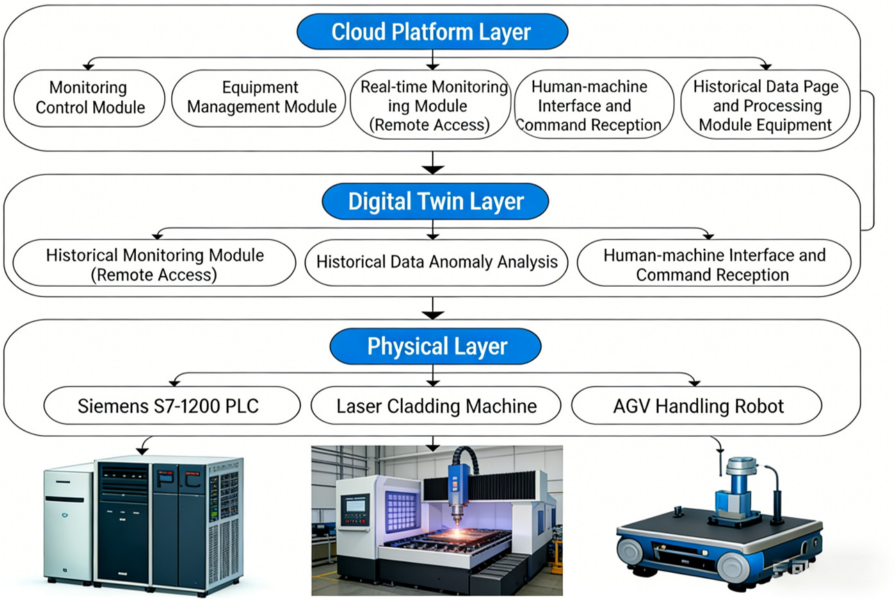

Figure 6. Communication Implementation Framework of Laser Cladding Cloud System

In digital twin systems, real-time data exchange between virtual simulation environments and underlying control systems constitutes the core component. Plant Simulation and PLC communication are achieved through a bidirectional connection between an OPC UA server (on the PLC side) and a client (on the simulation side). The system establishes a three-tier communication architecture comprising the "simulation layer, control layer, and device layer," employing a hybrid protocol of "OPC UA + Modbus TCP" to complete the closed-loop data flow for virtual simulation, logical control, and physical execution. The communication framework of the laser cladding cloud system is illustrated in Figure 6.

1. OPC UA Server Configuration on the PLC Side

Taking the Siemens S7-1200 PLC as the control core, enable the OPC UA server within TIA Portal. Configure an IP address within the same LAN as the simulation terminal and define a custom namespace (e.g., ns=1; s=LaserCladding_System). Set variable read/write permissions and device diagnostic functions. Physically network the PLC and the simulation terminal via an industrial Ethernet switch to ensure low-latency data interaction.

2. OPC UA Client & Variable Mapping on the Plant Simulation Side

Connect to the PLC server (IP + Port 4840) using the "OPC UA Client" interface and embed this client within the simulation framework. On the PLC side, categorize and define variables (BOOL-type status/instructions, REAL-type process parameters) under the "Input Signals, Output Commands, and Process Parameters" and mount them to the namespace. On the simulation side, bind virtual module properties to PLC variables via the "Browse" function (e.g., bind the virtual unit's IsProcessing to the PLC input I_Machining_Status). Set a refresh rate of 100ms along with an automatic plus trigger-based synchronization mechanism to guarantee real-time response for critical signals.

3. Modbus TCP Communication Configuration between PLC and Physical Devices

Adopt a Client/Server (C/S) architecture for communication between the PLC and physical devices (e.g., robots, laser cladding machines). Configure the device IPs (Port 502) using the Modbus TCP Client module in TIA Portal, and map PLC variables to device I/O registers according to the register mapping table (e.g., map robot joint angles to Holding Registers). The simulation terminal is logically isolated from the physical device network, relaying data exclusively through the PLC to prevent conflicts.

4. Communication Loop Closure Verification

After starting both the simulation and the PLC, verify the loop via the "Virtual-Control-Physical" closed-loop test: Plant Simulation sends a "Material in Position" signal, which is received by the PLC via OPC UA and subsequently issued to the robot via Modbus TCP. After the physical device executes the command, it feeds back data to the PLC, which is then synchronized to the virtual model to ensure state consistency. Verify data flow direction using variable monitoring tables and simulation signal lists to confirm link stability and real-time performance, ensuring closed-loop interaction between virtual simulation and physical production.

4. CLOUD PLATFORM SYSTEM CONFIGURATION PROCESS

The cloud platform configuration centers on three key steps: "Device Connection - Data Forwarding - Platform Visualization." First, configure the on-site data acquisition gateway. Connect your computer to the gateway's LAN port using an Ethernet cable, then enter the gateway's IP address (e.g., 192.168.1.100) into the computer's browser and log in using the default credentials. After logging in, create an acquisition channel within the gateway configuration tool, select the appropriate driver (such as Modbus TCP), and set the IP address and port number of the remote device. Next, create a new device under this channel and configure the data tags (refer to Figure 7), assigning a name, register address, and data type (e.g., Integer or Float) to each data point requiring collection. After completing the configuration, save the settings and restart the application to view the collected real-time data in the data monitoring interface.

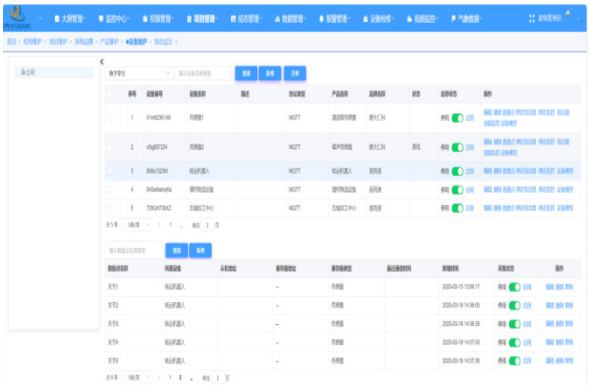

Figure 7. Cloud Platform Project Creation

Figure 8. Cloud Platform Dashboard View

Second, configure the gateway to forward the collected data to the cloud platform. Access the "Forwarding Service" in the gateway configuration tool and create a new forwarding channel. Select the driver type as "BonuoMqtt". The key configuration parameters must correspond to the information on the cloud platform side, including the MQTT server address (i.e., the IP of the cloud platform computer, e.g., 192.168.1.120), port (1883), username, password, subscription topic, and publishing topic. These parameters are obtained by adding a new device with the protocol type "Third-party MQTT" in the cloud platform's "Device Maintenance" section. Within the gateway's forwarding channel, create new data tags and select the acquisition points to be forwarded. Similarly, save the configuration and restart the application to activate the forwarding.

Finally, configure the device, data points, and visualization on the cloud platform side. Open the cloud platform (access via a browser, e.g., 192.168.1.120:3000). First, create the corresponding company and project within "Permission Management" and "Project Management". Then, add a device in "Device Maintenance", fill in the device name and brand, and select "Third-party MQTT" as the protocol type. The system will automatically generate the device code and credentials (username, password, etc.) required for MQTT connection. Next, add data points for this device, fill in the data point name, and link it to the data tag name configured during gateway forwarding in the "Variable Name" field (e.g., in the format p.dv.demo). Once the data points are added, proceed to "Configuration Management" for visualization design. Create monitoring screens by dragging components and binding them to the data points. The designed configuration diagrams can be published and viewed in the "Large Screen Management" section to see the final data visualization display, as shown in Figure 8.

5. CONCLUSION

Addressing the technical bottlenecks of traditional laser cladding systems, this study successfully developed an intelligent manufacturing cloud control system based on Digital Twin technology. The system establishes a three-tier architecture—integrating "Physical Equipment, Digital Twin, and Cloud Platform"—to achieve full-process data integration and real-time interaction. By breaking through key technologies such as digital twin modeling, cross-system data exchange, and remote intelligent control, this research provides a comprehensive technical solution for the intelligent upgrade of laser cladding processes. It not only overcomes the limitations of conventional systems but also paves the way for the transformation of the manufacturing industry from standalone automation to cloud-based collaboration, demonstrating significant engineering application value and theoretical innovation.

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Project Number: 202510066117

Tianjin Science and Technology Program — Cooperation Project between Tianjin and the Chinese Academy of Sciences (CAS)

Project Title: Development of Posture Variation Mechanism and Precision Intelligent Control Technology for Ultra-Minimally Invasive Robotic Puncture Components

Project Number: 25YFYSHZ00250

Tianjin Science and Technology Program — Cooperation Project between Tianjin and the Chinese Academy of Sciences (CAS)

Project Title: R&D of an Embodied Intelligent Mobile Robot Machining and Inspection System for Large-Scale Complex Components

Project Number: 24YFYSHZ00180

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