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# Optimization of Robotic Welding Processes Using Digital Twin Technology

Sh. S. Djurayev
D. M. Nabijonov
M. M. Abdumajidova
Namangan State Technical University
dilshodjonnabijonov1003@gmail.com

**Abstract**

**Digital twin (DT) technology has emerged as a transformative approach in modern manufacturing. In robotic welding processes, the adoption of DT enables real-time monitoring, process optimization, and predictive maintenance. This paper presents a systematic approach to optimizing robotic welding through digital twin integration. A digital replica of the robotic welding cell was created, enabling simulation and optimization of welding parameters. Results demonstrate significant improvements in welding precision, process stability, and defect reduction. The proposed approach offers a promising pathway for intelligent manufacturing systems.**

**Keywords: Digital Twin, Robotic Welding, Process Optimization, Intelligent Manufacturing, Real-time Monitoring.**

## Introduction

### 1.1 Background

The increasing demand for high-quality welded products in industries such as automotive, aerospace, and construction has led to the widespread adoption of robotic welding systems. These systems offer significant advantages over manual welding, including higher repeatability, greater throughput, and reduced labor costs. However, maintaining consistent weld quality in dynamic production environments remains a challenge due to variations in material properties, equipment wear, and process disturbances.

Digital twin technology, which creates a dynamic virtual replica of physical systems, provides new opportunities to overcome these challenges. By integrating real-time sensor data with simulation models, digital twins enable predictive analysis, adaptive control, and continuous optimization of manufacturing processes.

### 1.2 Motivation

Traditional robotic welding relies on pre-programmed trajectories and fixed process parameters, which may not be optimal under varying production conditions. In contrast, digital twin-driven approaches allow welding parameters to be continuously updated based on real-time feedback, resulting in improved weld quality and process robustness.

### 1.3 Objective
The primary objective of this study is to develop a digital twin framework for robotic welding systems and evaluate its impact on process optimization, weld quality, and operational efficiency.

### 1.4 Research questions
This study addresses the following research questions:
- How does digital twin integration affect welding precision and defect rates?
- Can digital twins enable adaptive control in robotic welding processes?
- What are the computational and data integration requirements for effective DT deployment?

## 2. Methods
### 2.1 System architecture
The digital twin architecture developed for this study comprises three main layers:
- **Physical layer:** A KUKA KR 16 robotic manipulator equipped with a Fronius TPSi welding source was used for the experiments. The robot performed MIG/MAG welding operations on mild steel workpieces.
- **Virtual layer:** A high-fidelity simulation model of the robotic welding cell was developed using Siemens Tecnomatix Process Simulate. The model included kinematic, thermal, and process dynamics representations.
- **Data layer:** Real-time data acquisition was implemented using OPC UA protocol, enabling bidirectional data flow between the physical system and the virtual model.

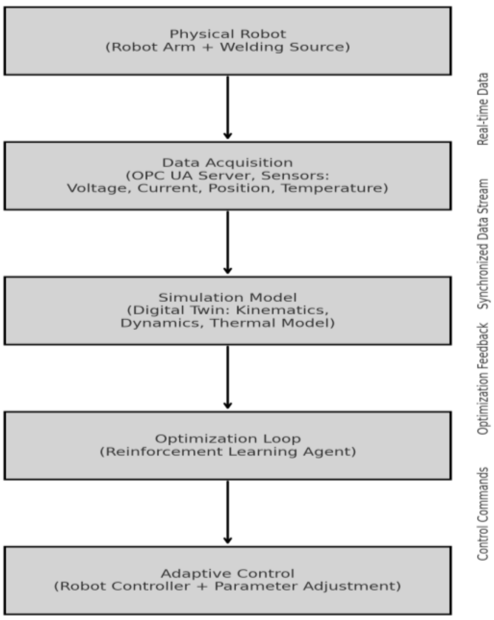


**Figure 1.** Digital twin architecture for robotic welding.

### 2.2 Data acquisition

To ensure accurate synchronization between the physical and virtual systems, the following process parameters were continuously monitored and recorded:

- Welding voltage (V)
- Welding current (A)
- Wire feed rate (mm/s)
- Robot joint positions (degrees)
- Torch speed and orientation (mm/s, angles)
- Weld pool temperature (°C) using infrared sensors

### 2.3 Optimization algorithms

The digital twin utilized a reinforcement learning (RL) framework to optimize welding parameters. The RL agent interacted with the virtual model to explore the parameter space and identify optimal settings.

The optimization objectives included:

- Minimizing geometrical deviations (bead width, height, penetration depth)
- Reducing spatter and porosity defects
- Enhancing process stability (minimizing current and voltage fluctuations)

The agent used Proximal Policy Optimization (PPO) algorithm with reward functions based on:

- Target weld geometry adherence
- Defect detection feedback
- Process energy efficiency

### 2.4 Experimental setup

Experiments were conducted on lap joint configurations using 5 mm thick mild steel plates. The experimental protocol involved three scenarios:

1. **Baseline:** Conventional welding with fixed pre-programmed parameters.
2. **DT-based offline optimization:** Parameters optimized in the virtual model and then applied to the physical robot.
3. **DT-based online adaptive optimization:** Real-time adaptive control using the digital twin feedback loop.

Each scenario was repeated for 100 weld cycles to ensure statistical significance.

## 3. Results

### 3.1 Welding Precision

**Table 1.** Weld Bead Width Deviation (Target Width = 6 mm)

| Scenario | Mean deviation (mm) | Std. Dev. |
|---|---|---|
| Baseline | 0.85 | 0.32 |
| DT-based offline optimization | 0.35 | 0.12 |
| DT-based online adaptive optimization | 0.22 | 0.08 |

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The DT-based adaptive control reduced the average weld bead width deviation by 74% compared to the baseline.

### 3.2 Defect Rate

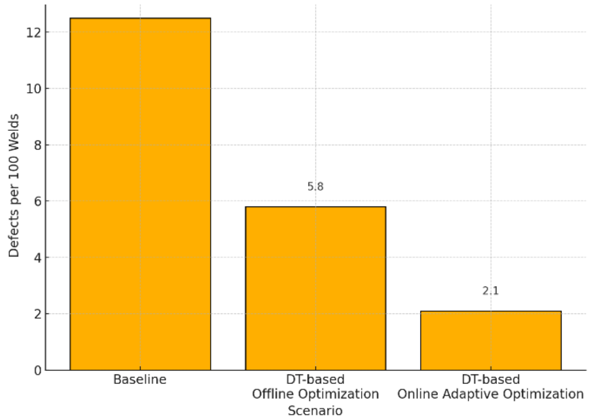


**Figure 2.** Defect rate comparison across scenarios

| Scenario | Defects per 100 Welds |
|---|---|
| Baseline | 12.5 |
| DT-based offline optimization | 5.8 |
| DT-based online adaptive optimization | 2.1 |

The defect rate was reduced by 83% with online DT optimization.

### 3.3 Process stability

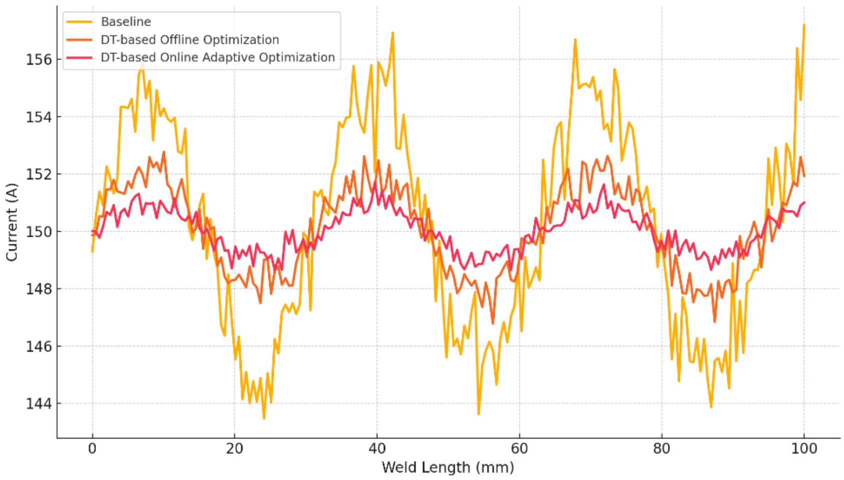


**Figure 3.** Current fluctuation over weld length

Graph showing RMS current fluctuation for each scenario:

- Baseline → ±5A
- Offline DT → ±2A
- Online DT → ±1A

Improved process stability leads to better energy control and weld consistency.

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### 3.4 Computational Performance

**Table 2.** DT Optimization Loop Latency

| Component | Latency (ms) |
|---|---|
| Simulation Step | 100 |
| Data Synchronization | 50 |
| Total Loop Time | 150 |

The 150 ms total loop latency was sufficient for real-time adaptive control in typical industrial robotic welding applications.

## 4. Discussion

The integration of digital twin technology in robotic welding demonstrated significant benefits in terms of weld quality, process stability, and defect reduction. The ability of the DT to continuously adapt parameters in response to real-time sensor feedback resulted in superior performance compared to static, pre-programmed approaches.

### 4.1 Implications for Industry

The use of DT in robotic welding aligns with the Industry 4.0 paradigm, promoting smart manufacturing practices. Enhanced process adaptability reduces scrap rates, improves first-pass yield, and enables rapid adaptation to new product variants.

### 4.2 Challenges and Limitations

Several challenges were encountered during implementation:

- High computational requirements for accurate thermal and fluid dynamics simulation.
- The need for precise calibration of sensors and virtual models.
- Integration complexity with legacy robotic systems.

### 4.3 Future Work

Future research will focus on:

- Extending the DT framework to multi-robot collaborative welding cells.
- Incorporating metallurgical models for microstructure prediction.
- Deploying DT-based predictive maintenance for robotic welding equipment.

## 5. Conclusion

Digital twin technology offers a powerful tool for optimizing robotic welding processes. This study demonstrated that DT integration enables adaptive control, improves weld precision, and reduces defect rates. The results suggest that DT-driven robotic welding can significantly enhance manufacturing efficiency and product quality. Further development and broader industrial adoption of this technology are anticipated to drive the next wave of intelligent robotic manufacturing.

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