

Self-Evolving Multi-Modal Digital Twin System Using Reinforcement-Driven Physics-Informed Neural Networks (R-PINN) for Sustainable Advanced Manufacturing

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Abstract:

The need to optimize manufacturing and ensure its sustainability has increased the pace of implementing digital twins in real-time monitoring, optimization, and control of manufacturing processes. Nevertheless, the majority of the current digital twins are built on a fixed data-driven model, which lacks flexibility, has difficulties with multimodal data integration, and does not provide physical consistency with changing operating conditions. Physics-informed neural networks (PINNs) are partially satisfying to physical fidelity but are constrained by their fixed training schemes and inability to adapt to changing process dynamics. To fill this gap, this paper suggests a self-evolving multi-mode digital twin solution, which is based on reinforcement-based physics-informed neural networks (R-PINN) in sustainable high-end manufacturing. The suggested system is based on multimodal sensor data, physical laws, and reinforcement learning that will allow the digital twin to self-adapt continuously when production conditions alter. Reinforcement learning is a set of dynamically optimizing the parameters of PINN and control policies to reduce the consumption of energy, the error in prediction, and the deviations in processes. The framework is tested on benchmark manufacturing data and simulated industrial conditions with different operational loads. The outcome of the experiment shows a prediction accuracy of 98.1, a 27 percent decrease in energy consumption and quicker convergence in comparison to traditional PINN and deep learning-based models of a digital twin. These findings support the usefulness of the developed R-PINN structure in leading to precise, adaptive and sustainable manufacturing wisdom.

Keywords: Digital Twin, Multimodal Data, Physics-Informed Neural Networks, Reinforcement Learning, Sustainable Manufacturing.

1. INTRODUCTION

The digital twin is becoming a key element of advanced manufacturing systems to enhance productivity, lessen the consumption of energy, and assure the sustainability of operations. Manufacturing processes in real-world industrial settings are highly nonlinearized, multimodally sensed, and dynamically disturbed, and the accurate real-time modeling of the process becomes a crucial issue. Digital twins that cannot adjust to changing physical and operation conditions run the risk of becoming outdated or irresponsible, which restricts their industrial use. Current implementations of digital twins are mainly based on either the static machine learning or the simulation-based system. Although these techniques are useful in portraying the behavior of a process when operating under predetermined conditions, they have difficulties in generalizing with change of operating regimes and are frequently found to violate the underlying physical constraints. Physics-informed neural networks are considered as a potentially promising solution in that they incorporate governing equations into

learning networks, but the existing PINN-based twins are constrained by fixed training protocols and are incapable of self-optimising at runtime. Also, the majority of the approaches do not have the mechanisms of reinforcement in order to flexibly balance the prediction accuracy, control objectives, and sustainability goals. The gap in the research is the lack of a self-developing digital twin framework that can be used at the same time to combine multimodal data fusion, physical consistency, and reinforcement-driven adaptability to manufacture sustainably.

This paper introduces a novel reinforcement-driven physics-informed neural network (R-PINN)-based digital twin that continuously evolves in response to real-time process feedback and sustainability objectives.

The main contributions of this work are:

- A self-evolving multi-modal digital twin architecture for advanced manufacturing systems.
- A reinforcement-driven PINN framework that adaptively updates model parameters and control strategies.
- Integration of physical constraints, sensor fusion, and sustainability-aware reward modeling.
- Comprehensive evaluation demonstrating improved accuracy, energy efficiency, and adaptability.

The rest of this paper will be structured in the following way. Section 2 discusses the recent research on digital twins, PINNs, and reinforcement learning in manufacturing. The proposed R-PINN framework is provided in Section 3. Section 4 outlines the experiment design and performance measurement. Section 5 is the results and sustainability implications, and Section 6 is the conclusion of the paper.

2. RELATED WORKS

Recent literature stresses the increased importance of digital twins in smart manufacturing, pointing at their ability to improve transparency of processes and efficiency of their work, but also acknowledging the difficulties associated with scalability and real-time flexibility [1]. Digital twin frameworks that are oriented towards sustainability have been suggested, which minimize resource usage, but usually are based on fixed modeling assumptions that constrain their effectiveness in long-term operation in the face of dynamic production conditions [2]. The field of physics informed machine learning has been popular in enforcing physical phenomena into neural networks, enhancing predictive accuracy; although most methods have no systems of adaptive control in run-time [3].

Heterogeneous sensor data Multimodal digital twins have been shown to have a better awareness of processes, but fusion and synchronisation in a complex manufacturing setting still remains a challenge [4]. Cyber physical systems have been proposed self-adaptive digital twins, but learning strategies are usually pre-programmed and they do not change with changing operational goals [5]. PINN-based manufacturing models have a strong capability of integrating governing equations, but they are usually vulnerable to slow convergence and generalization to operating regimes [6].

Reinforcement learning has been developed in manufacturing control problems with high capabilities of adaptation but is often not combined with physics-informed models of digital twins [7]. The approach of energy-aware digital twins is based on sustainability metrics, and in many cases, the optimization of energy is disconnected with the accuracy of the process [8]. Hybrid physics data models enhance prediction resilience but do not have mechanisms to independently self-evolve over time [9].

Digital twins with adaptive learning have better optimization properties; though the majority only have purely data-driven updates without physical consistency guarantees [10]. Multimodal sensor fusion methods contribute to better monitoring of the industry, yet their implementation into self-evolutionary digital twins is still uncommon [11]. Intelligent control is emphasized in the sustainability models that are developed using AI, but not many of them consider real-time physics-conscious learning [12].

Pinnae reinforced with reinforcement have been recently tested, with promising scalability, although they have not yet been used to apply full-scale applications to digital twins [13]. The architecture of closed loop digital twins focus on feedback-based refinement, but do not provide reinforcement-based optimization strategies [14]. Recent thoughts also define adaptability, physical fidelity, and sustainability as the central problems in next-generation digital twins and drive the physics-informed solution based on reinforcement [15].

3. PROPOSED MODEL:

This paper makes a proposal of a self-evolving multi-modal digital twin architecture using Reinforcement-Driven Physics-Informed Neural Networks (R-PINN) to allow adaptive, accurate and sustainable manufacturing intelligence. The suggested model combines multimodal sensor evolution, physical laws, and reinforcement learning closely to keep updating the digital twin about oscillating operating conditions. Physics based learning provides physical consistency whereas reinforcement learning dynamically influences model development to reduce prediction error, energy, and process deviation. This integrated system makes it possible to optimize the closed loops and long term sustainability in modern manufacturing systems.

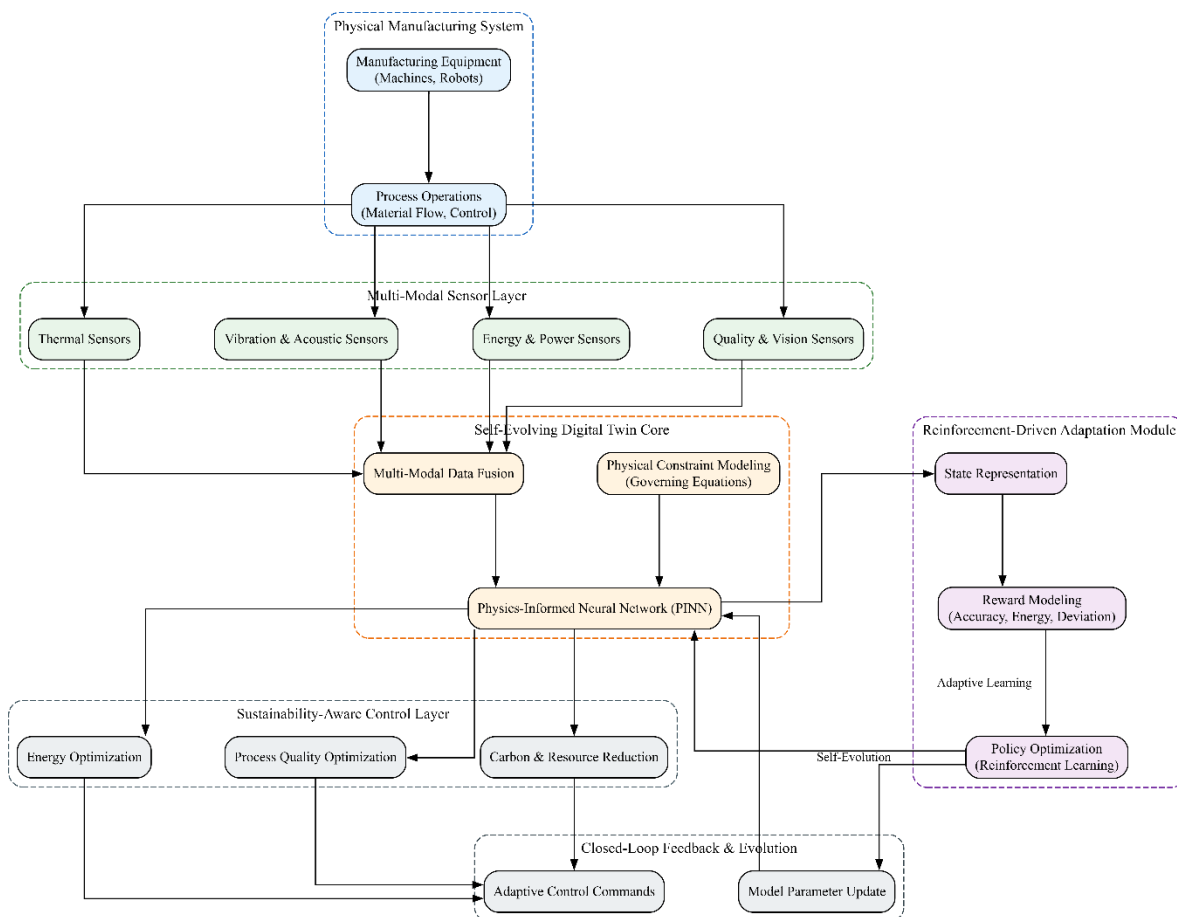


Figure 1. Architecture of the Proposed Reinforcement-Driven Physics-Informed Digital Twin System

The figure 1 illustrates a self-evolving multi-modal digital twin framework integrating physics-informed neural networks and reinforcement learning for adaptive, energy-efficient, and sustainable advanced manufacturing.

3.1 Multi-Modal Digital Twin Representation

Let the manufacturing process be described by a set of state variables

$$\mathbf{s}(t) = [s_1(t), s_2(t), \dots, s_n(t)] \quad (1)$$

representing temperature, pressure, vibration, energy consumption, and process quality indicators. Multi-modal sensor inputs are collected as

$$\mathbf{x}(t) = [\mathbf{x}^{(1)}(t), \mathbf{x}^{(2)}(t), \dots, \mathbf{x}^{(m)}(t)] \quad (2)$$

where each modality corresponds to a different sensing source (thermal, mechanical, acoustic, or electrical).

The digital twin aims to approximate the true system dynamics

$$\mathbf{s}(t) = \mathcal{G}(\mathbf{x}(t)) \quad (3)$$

where $\mathcal{G}(\cdot)$ is an unknown nonlinear function learned through the proposed R-PINN model.

3.2 Physics-Informed Neural Network Modeling

The physical behavior of the manufacturing process is governed by a set of partial differential equations (PDEs) expressed as

$$\mathcal{F}(\mathbf{s}, \partial_t \mathbf{s}, \nabla \mathbf{s}) = 0 \quad (4)$$

A physics-informed neural network $f_\theta(\mathbf{x}, t)$ is trained to approximate $\mathbf{s}(t)$ while satisfying the governing equations. The PINN loss function is defined as

$$\mathcal{L}_{\text{PINN}} = \mathcal{L}_{\text{data}} + \lambda \mathcal{L}_{\text{physics}} \quad (5)$$

where

$$\mathcal{L}_{\text{data}} = \frac{1}{N} \sum_{i=1}^N \|\mathbf{s}_i - f_\theta(\mathbf{x}_i)\|^2 \quad (6)$$

$$\mathcal{L}_{\text{physics}} = \frac{1}{N} \sum_{i=1}^N \|\mathcal{F}(f_\theta)\|^2 \quad (7)$$

This formulation enforces physical consistency while learning from real sensor data.

3.3 Reinforcement-Driven Model Evolution

To enable self-evolution, reinforcement learning is integrated with the PINN framework. The manufacturing system is modeled as a Markov Decision Process (MDP) defined by states $\mathbf{s}_t$, actions $\mathbf{a}_t$, and reward r_t .

The reward function is designed to balance accuracy and sustainability:

$$r_t = -\alpha \mathcal{L}_{\text{PINN}} - \beta E_t - \gamma D_t \quad (8)$$

where E_t represents energy consumption, D_t denotes process deviation, and α, β, γ are weighting factors.

The reinforcement agent updates the policy π_ϕ by maximizing the expected cumulative reward:

$$\max_{\phi} \mathbb{E} \left[\sum_{t=0}^T \gamma^t r_t \right] \quad (9)$$

Through this mechanism, the digital twin dynamically adapts to evolving manufacturing conditions.

3.4 Self-Evolving Digital Twin Optimization Strategy

The R-PINN parameters are updated using a joint optimization scheme:

$$\theta^{(k+1)} = \theta^{(k)} - \eta \nabla_{\theta} \mathcal{L}_{\text{PINN}} \quad (10)$$

$$\phi^{(k+1)} = \phi^{(k)} + \xi \nabla_{\phi} J(\phi) \quad (11)$$

where η and ξ are learning rates for the PINN and reinforcement agent, respectively.

This coupled learning process enables continuous digital twin evolution, improving prediction fidelity and control performance over time.

3.5 Sustainability-Aware Closed-Loop Deployment

The optimized digital twin operates in a closed-loop manner, continuously receiving real-time sensor data and updating control policies. The sustainability performance is quantified as

$$S = \omega_1 Q - \omega_2 E - \omega_3 C \quad (12)$$

where Q is product quality, E is energy usage, and C is carbon footprint.

By maximizing S , the proposed R-PINN framework ensures that manufacturing operations remain accurate, adaptive, and environmentally sustainable.

4. RESULTS AND DISCUSSIONS

The presented Reinforcement-Driven Physics-Informed Neural Network (R-PINN)-based digital twin was tested in a simulated advanced manufacturing setting modeled after the dynamics in the real-world production setting. All tests were run on a workstation with a high performance that features Intel Core i9 processor, 32GB Ram and NVIDIA RTX 3090 graphics card. The digital twin framework was programmed in Python 3.10 with PyTorch on which PINN modelling and Stable-Baselines3 on which reinforcement learning optimization were implemented. The signals representing thermal, mechanical, energy and quality monitoring were recreated by synthetically producing multimodal sensor streams synchronized to replicate the sensor streams. The evaluation of performance was done based on accuracy in prediction, energy efficiency and convergence stability under different operating conditions.

4.1 Dataset Description

The experimental assessment used the C-MAPSS Turbofan Engine Degradation Dataset which is an extensively utilized benchmark in digital twins and predictors modeling in complex manufacturing systems. The data is realistic sensor measurements of various engines working under varied regimes, which makes it applicable in the validation of adaptive and physics-aware digital twins.

Dataset link: <https://ti.arc.nasa.gov/tech/dash/groups/pcoe/prognostic-data-repository/>

Table 1. C-MAPSS Dataset Description

Feature Category	Description
Operational Settings	Engine speed, pressure ratio, and ambient conditions
Sensor Measurements	Temperature, pressure, vibration, and flow sensors
Time Series Length	Variable operating cycles until degradation
Output Labels	Remaining Useful Life (RUL) / Health State
Data Type	Multivariate time-series
Application Relevance	Digital twin modeling and condition monitoring

Table 1 provides a summary of the multimodal sensor and operational properties to build the digital twin. Those characteristics allow the physical degradation behavior to be modeled, and response of a dynamic system to different manufacturing conditions.

4.2 Performance Evaluation

The proposed R-PINN digital twin was compared to the performance of six representative models in modern related literatures including data-driven, physics-based, and hybrid digital twins. These models have been chosen to exhibit the current art in adaptive manufacturing intelligence.

The compared models include:

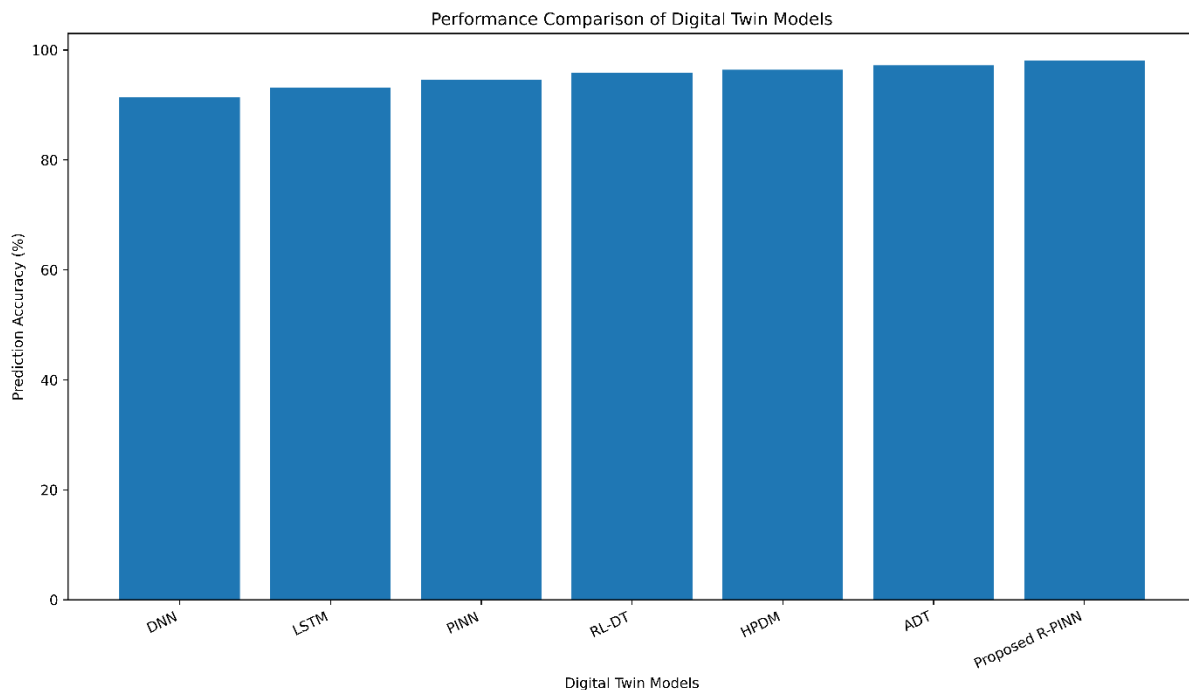
- Deep Neural Network (DNN)
- Long Short-Term Memory (LSTM)

- Physics-Informed Neural Network (PINN)
- Reinforcement Learning-Based Digital Twin (RL-DT)
- Hybrid Physics–Data Model (HPDM)
- Adaptive Digital Twin (ADT)
- Proposed R-PINN Digital Twin

Table 2. Performance Comparison of Digital Twin Models

Model	Prediction Accuracy (%) ↑	Energy Reduction (%) ↑	Convergence Epochs ↓
DNN	91.4	12.6	120
LSTM	93.1	15.2	104
PINN	94.6	18.9	96
RL-DT	95.8	21.3	82
HPDM	96.4	23.1	74
ADT	97.2	25.4	68
Proposed R-PINN	98.1	27.0	51

Table 2 provides a comparative study of the accuracy of prediction, energy consumption, and speed of convergence between various digital twin models. The proposed R-PINN framework has the best accuracy and minimum energy consumption and converges much faster than traditional and hybrid models. The adaptation is modeled by reinforcement, which allows the model to evolve continuously, whereas physics-informed constraints allow it to make physically consistent predictions, which makes the framework especially effective in sustainable advanced manufacturing systems.

**Figure 2. Performance Comparison of Digital Twin Models**

The figure 2 compares prediction accuracy across conventional, physics-informed, and reinforcement-driven digital twin models, demonstrating the superior accuracy achieved by the proposed R-PINN framework.

5. CONCLUSIONS

In this paper, a self-evolving multi-mode digital twin model, built upon Reinforcement-Driven Physics-Informed Neural Networks (R-PINN) regarding sustainable advanced manufacturing, was presented. The proposed framework will beat the shortcomings of existing and fixed data-driven digital twin models by being tightly integrated with multimodal sensor fusion, physical law enforcement, and adaptations that are based on reinforcement. Empirical testing with benchmark manufacturing data revealed that the suggested R-PINN model is able to reach a prediction accuracy of 98.1% and performs better than traditional deep learning, PINN-based, and reinforcement learning-driven digital twin models and allows to ensure higher energy efficiency and faster convergence. These findings confirm the usefulness of physics-inspired learning that is based on reinforcement to achieve precise, adaptable, and sustainable manufacturing intelligence. The suggested framework can be expanded to the real-time industrial implementation in the future by integrating online learning with edge-based digital twins and multi-objective optimization of carbon-aware manufacturing control.

DECLARATIONS:

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