# Implementation of a Digital Twin for Wire Arc Additive Manufacture

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## Abstract

In this paper, the authors describe the design, implementation and testing of a prototype digital twin of a manufacturing cell that can be used for wire arc additive manufacture. We have used Nvidia's Omniverse as the core platform due to its open interface, which facilitates easy integration with open-source and proprietary CAD, CAM and CAE tools. The digital twin breaks down the functional silos between design, manufacture, operations and maintenance, providing a full digital thread of the processes and a digital passport for the component. The implementation collects, stores and links all data associated with a manufactured part. Using the manufacture of a fusion power plant component as a case study, interaction with the digital twin starts with the engineer creating the original CAD model. Once complete, the CAD model is processed (by software) to prepare instructions for a robot arm to build the part. The manufacturing cell is equipped with various sensors and cameras. All the instrument data is streamed to the digital twin as the build progresses. To facilitate a loop back from manufacturing to physics-based modelling, a layer-by-layer build geometry is digitised using a laser scanner mounted to a second robot arm. The geometry is passed to a proprietary finite element package for meshing and residual stress analysis. All data captured by the twin is processed and documented, employing automation where possible, reducing the need for human involvement. After installation in the fusion power plant, the complete digital record can be retrieved at any time during the lifetime of the component. If the power plant is instrumented, the operating conditions can also be streamed to the digital twin, informing maintenance schedules. The digital twin links the traditional CAD/CAE design process with the actual cradle-to-grave experience of the component, allowing engineers to re-evaluate assumptions made at the design concept stage, as well as providing the opportunity for lessons learned, informing design for future generations of power plants.

## 1. Introduction

Digital Twin (DT) technology is an effective tool for improving manufacturing processes by bridging physical entities and virtual environments via data exchange systems[1]. By integrating sensor data with advanced simulations, DTs enable process monitoring, optimization, and predictive analytics, ultimately enhancing manufacturing efficiency and quality[2]. While DT applications have been successfully implemented in industries such as urban management, logistics, and construction[3], their potential in additive manufacturing remains an area of active exploration.

Wire Arc Additive Manufacturing (WAAM), a form of Direct Energy Deposition-Arc (DED-Arc) technology, presents unique adaptability for high-value, low-volume components. WAAM utilizes an electric arc to melt wire feedstock, which is deposited in a desired metallic pool to construct a near-net-shape structure[4]. Compared to powder bed fusion (PBF), WAAM offers higher deposition rates, making it a preferred choice for manufacturing large-scale metal components. Additionally, WAAM is highly material-efficient, reducing waste and offering cost advantages for industries dealing with expensive materials such as titanium, nickel-based alloys, and high-strength steels. The advantages of WAAM make it particularly attractive for critical applications in aerospace, nuclear energy, maritime, and defence industries[4-7], where components are often complex, costly, and produced in limited quantities. This is particularly the case for the nascent fusion power industry.

However, despite its potential, WAAM presents significant challenges in process control and quality assurance. The mechanical properties of WAAM components can be influenced by factors such as feedstock composition, deposition parameters, thermal history, and residual stress[8]. These uncertainties highlight the necessity of a robust DT framework to facilitate real-time process monitoring, data-driven optimization, and predictive modelling.

The use of NVIDIA Omniverse$^{TM}$ to develop a digital twin framework that integrates CAD, CAM, and CAE for wire arc additive manufacturing is described. The approach taken enables collaborative design, automated manufacturing code generation, virtual testing, and real-time production monitoring. In-process data acquisition has been linked to physical manufacturing with simulation-driven insights. By unifying data across the entire lifecycle—from initial design to in-service operation—this digital twin enhances process transparency, traceability, and optimization. A case study on a single deposition demonstrates its practical implementation and potential impact on future engineering workflows.

## 2. Manufacturing System and Process Overview

Wire Arc Additive Manufacturing (WAAM) is a metal additive manufacturing technique that utilizes an electric arc to melt and deposit feedstock wire layer by layer. The specific deposition technology applied was an advanced Gas Metal Arc Welding or Metal Inert Gas (GMAW/MIG). Similar to standard fusion welding, a continuous metal wire is fed towards a substrate. An applied voltage and current generate an arc and make the wire melt and form a molten pool. As the material solidifies, it gradually builds up the desired geometry[9] on a substrate. Throughout the process, a shielding gas is supplied to protect the molten metal from oxidation while also contributing to the formation of a stable plasma zone, promoting consistent deposition and metallurgical quality. The distinction between WAAM and fusion welding is that the former requires less energy input as a parent material does not require melting. Importantly, a WAAM implementation can be rapidly repurposed for fusion welding – as too is the digital twin which has been developed.

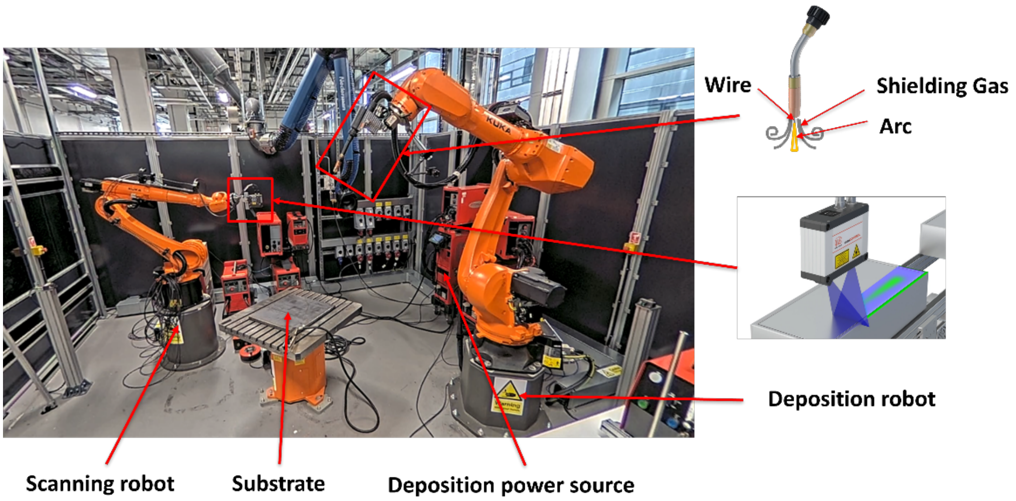


*Figure 1: The overview of the manufacturing unit, the deposition robot is used to lay down the materials to the substrate and the scanning robot is used to generate the real product shape in virtual space.*

As shown in *Figure 1*, the subject manufacturing cell consists of two collaborative robotic arms, each assigned a specific role in the additive manufacturing process. The deposition robot is responsible for precisely depositing metal material onto the substrate using direct energy deposition (DED). Its movements are guided by manufacturing instructions generated from CAD and CAM software, which are translated into KUKA Robot Language (KRL$^{TM}$) for execution.

After completing the deposition of a single layer, the system allows for a controlled cooling period. During this time, the scanning robot employs a laser scanner to perform a 3D scan of the manufactured part. The scan results are captured as a point cloud, providing a detailed representation of the actual geometry. This data serves as a basis for further analysis, which will be described subsequently.

## 3. Digital Twin Assisted Manufacturing

This section presents the application of our digital twin (DT) framework in the manufacturing of a representative 3D model geometry: the Stanford Bunny.

While the Stanford Bunny itself is not a fusion reactor component, its relatively complex geometry makes it an ideal benchmark for evaluating the capabilities of Wire Arc Additive Manufacturing (WAAM) in producing intricate structures. Given that many fusion reactor components, particularly thin-walled manifolds, feature similar geometric complexities, this study serves as a critical step in demonstrating WAAM's feasibility for such applications. Previous studies have also used the Stanford Bunny as an additive manufacturing benchmark[10].

### *1) Manufacturing challenges*

In the context of Wire Arc Additive Manufacturing (WAAM), one of the primary challenges in manufacturing the Stanford Bunny lies in its intricate geometry. The model's complex surface, with varying curvature and fine details, demands a high level of precision in controlling material deposition paths and rates. These geometric features closely resemble the structural characteristics of fusion reactor components, as shown in *Figure 2*, such as plasma containment system designs[11].

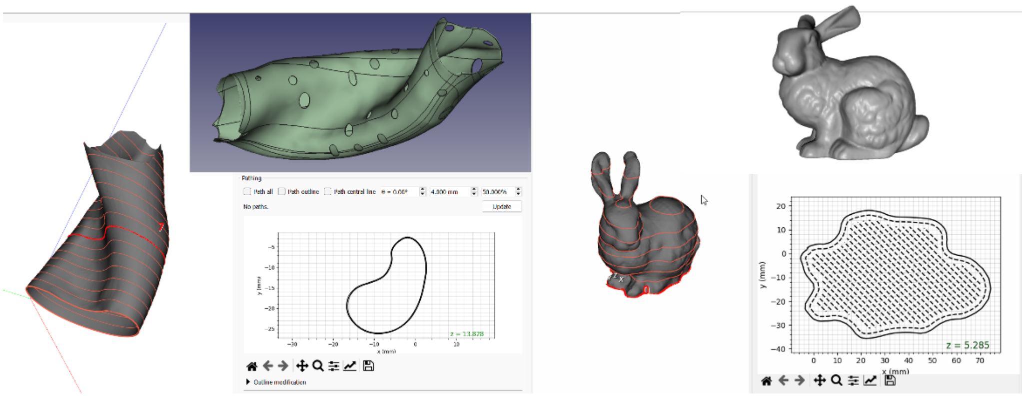


*Figure 2: Comparison of geometric complexity between the stellarator shape and the Stanford Bunny. Both models exhibit intricate contours and varying curvature, posing significant challenges for WAAM.*

Further, due to the layer-by-layer deposition process, thermal distortion and residual stresses are common issues, potentially leading to warping or dimensional inaccuracies. Maintaining a consistent surface finish without overbuilding or underbuilding the shell is another challenge, particularly when the thin walls of the structure require careful control over material flow and heat input.

Given the complexities associated with WAAM, the integration of a digital twin framework becomes essential in optimizing the manufacturing process of the Stanford Bunny. A digital twin—by incorporating CAD, CAM, and CAE—enables a seamless transition from design to production, ensuring that components are manufactured with the highest possible accuracy. Primarily, DT aggregates information from CAD files and the data points in KRL from the CAM unit. These results can then be compared with actual data obtained from a scanning robot, allowing for the rapid detection of dimensional defects. The recorded data forms a big dataset, which provides essential support for a data-driven manufacturing process. DT will not only improve part quality but also ensure greater reproducibility in WAAM processes[12].

*2) Digital Twin Architecture*

NVIDIA Omniverse™ is an open, extensible, multi-GPU collaboration platform designed for 3D design, simulation, and real-time collaboration. Built on the Universal Scene Description™ (USD) framework, it integrates AI, physics-based simulation, and advanced rendering technologies, enabling seamless interoperability between different software tools and teams. Omniverse™ is a collection of interconnected services, including cloud storage (Nucleus™), robotics simulation applications (Isaac Sim™), and development kits (Omniverse Kit™). These components provide essential support for DT development by offering data storage, user interface tools, and customizable integration services.

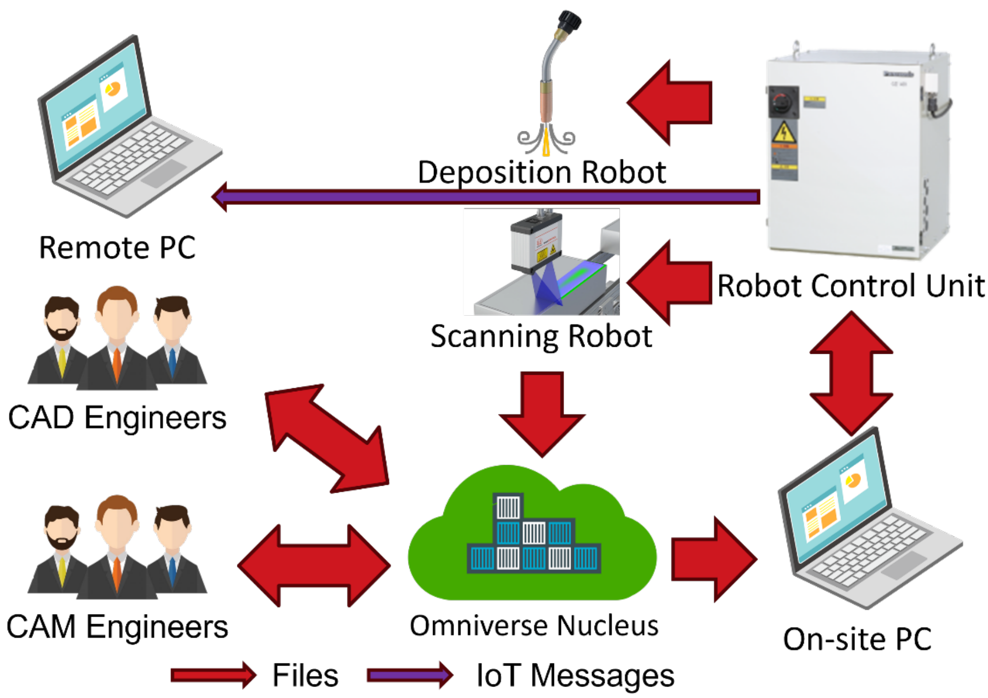


*Figure 3: CAD/CAM engineers can collaborate remotely by accessing 3D files stored in Nucleus cloud storage and transferring manufacturing files to an on-site PC. During the manufacturing process, the robot arm's parameters are transmitted to a remote PC equipped with a DT user interface via the IoT communication protocol, enabling real-time remote process monitoring.*

In this study, Omniverse is used for the construction of the digital twin (DT). As shown in *Figure 3*, CAD/CAM engineers can access 3D geometry stored in Nucleus through an extension developed in Isaac Sim™. This process enables remote collaboration by utilizing Omniverse™'s real-time editing capabilities for 3D USD files. After individually completing their edits, engineers can attach different tags to these files. The tag information includes details on who made the modification when it was made, and what changes were applied. This helps the engineering team with version control.

When CAM engineers generate KRL™ files, these files can also be transferred via Nucleus to an on-site PC connected to the manufacturing unit. The robotic arm executes material deposition or scanning based on the coordinates, welding parameters, and movement speeds contained in the KRL™ file. During the manufacturing process, the motion parameters of the robotic arm are transmitted to a remote server or terminal via the standard IoT communication protocol MQTT. The virtual manufacturing unit in Isaac Sim™ responds in real time according to these parameters. This enables a DT-assisted production workflow from CAD/CAM to manufacturing.

*3) Pre-production processing involving DT*

The conversion of Bunny's 3D file into the required files for the WAAM manufacturing unit follows. First, the 3D file needs to be sliced according to a specified layer height. The definition of the layer height must consider multiple factors, including material properties, wire feed rate, and robotic arm movement speed. These factors are determined by initial trials and can be stored in a database. The DT records and traces this metadata, which will serve as reference data for the slicing process in the future.

The slice data is then used to define the welding torch trajectory. Based on the generated data points, a program directly generates manufacturing instructions in accordance with the KRL file structure. These files are transmitted via Nucleus to the on-site PC and then submitted to the robotic arm for manufacturing. The 3D file processing flow refers to *Figure 4*.

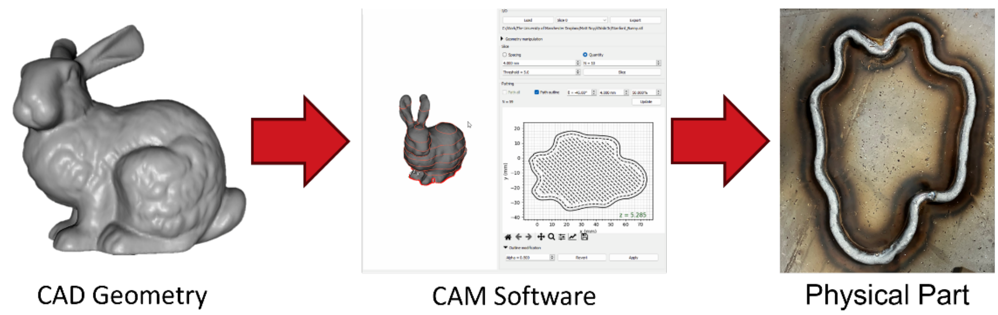

*Figure 4: DT integrates with CAD and CAM tools for cooperation from geometry to manufacturing code to physical part.*

### *4) Manufacturing and Process Monitoring*

The manufacturing execution process is guided by the KRL™ generated in the previous step. This program directs the robotic arm to deposit metal material onto the substrate along a predefined toolpath. During manufacturing, real-time motion data from the robotic arm is transmitted via MQTT. Additionally, remote clients can monitor the manufacturing process in real-time through the integrated process monitoring features in NVIDIA Omniverse™.

To further enhance process transparency and quality control, the manufacturing unit is equipped with both a welding pool camera and a safety camera. These cameras continuously capture process data, which is stored on an on-site computer. Selected data streams are also transmitted through Omniverse Nucleus™ to remote users, enabling playback and evaluation of past manufacturing operations.

After each layer of material is deposited, a laser scanner is used to scan the fabricated section. The collected data undergoes coordinate transformation to align with the robotic arm's coordinate system. Both the raw data and the processed point cloud are transmitted and stored using Nucleus. An essential feature of Nucleus is its ability to tag uploaded data with metadata such as user information, upload time, and custom annotations. This structured tagging system facilitates efficient data management and classification, ensuring traceability throughout the manufacturing process.

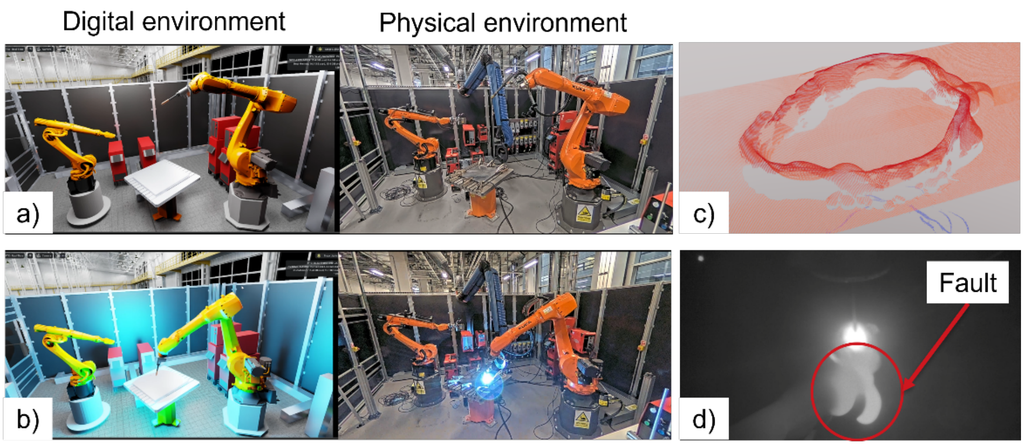


*Figure 5: a) Digital WAAM cell along with physical manufacturing unit. b) Streaming of robot motion and monitoring the manufacturing process. c) Laser scanner point cloud visualization. d) Logged fault by welding pool camera.*

All sensor data and manufacturing parameters collected throughout the WAAM process are stored within the digital twin framework, forming a comprehensive manufacturing dataset. Given the challenges associated with heat control and material deposition in WAAM, this dataset serves as a valuable resource for machine learning and big data analysis. This information can be used to dynamically adjust process parameters in real time, ensuring greater manufacturing stability and precision. Ultimately, this data-driven approach plays a crucial role in compensating for WAAM's inherent limitations in dimensional accuracy, to get a more reliable and refined additive manufacturing process.

## 4. Extensions and further applications

The DT framework serves as a crucial tool for computational analysis and process optimization in WAAM. By integrating recorded process parameters into CAE simulations, such as Finite Element Analysis [13], we establish a foundation for incorporating sensor-acquired data into simulation workflows. In this study, we demonstrate how scanned point cloud data of the welding bead shape as shown in *Figure 6* can be fitted and imported into meshing software, forming a pre-processing for subsequent thermal and residual stress simulations.

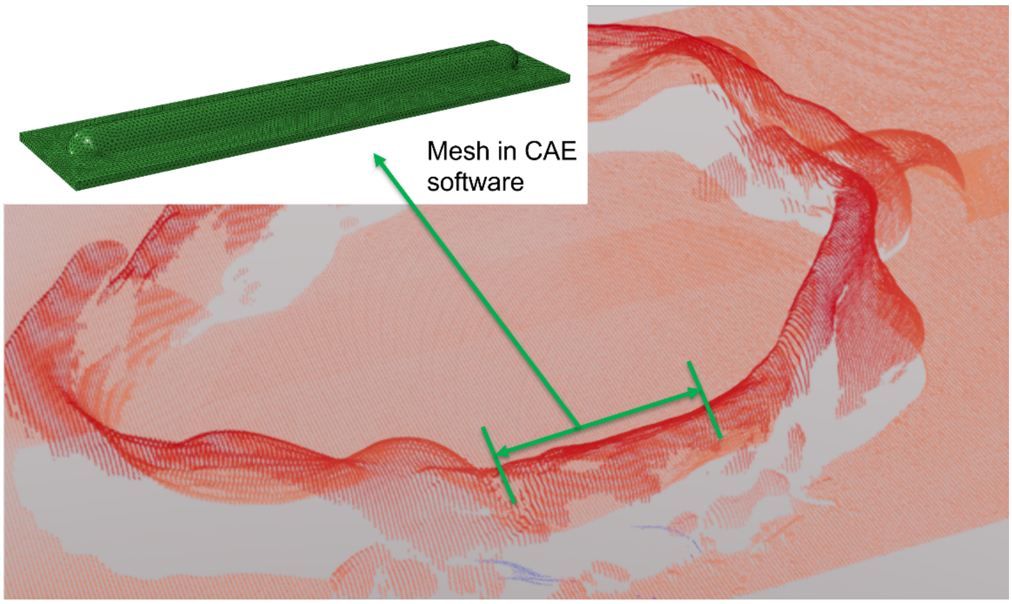


*Figure 6: Workflow for generating a CAD model from scanned point cloud data, which is processed through parabola fitting to extract geometric parameters. Then it can be used to form the physical dimension mesh for further finite element simulations.*

However, these simulations are computationally demanding, often requiring substantial processing power. Recent studies suggest that neural networks could accelerate predictive modelling [14], while high-performance computing may enable real-time layer-by-layer analysis within cooling intervals. Establishing a feedback loop between simulation results and manufacturing data could, in principle, refine process parameters dynamically. This highlights the potential role of DT in WAAM, enabling data integration, virtual-physical interaction, and informed decision-making in advanced manufacturing.

Beyond process optimization, DTs offer significant advantages in data record-keeping. A fully digital record of each manufactured component enables rapid retrieval of its full production history, including material properties, welding parameters, and robot configuration. This historical data can be invaluable for determining component longevity and even facilitating the rapid fabrication of replacement parts. Just as in nuclear fusion scenarios, where high-temperature and high-pressure conditions make the wear and tear of core components unpredictable. It may be uncertain due to the technology is still in the experimental stage. The core components of the reactor require continuous inspections and even periodic replacement[15]. These historical data enhance the ability to reproduce identical components. The ability to trace back to exact manufacturing parameters can enhance quality assurance.

## 5. Conclusion

This study demonstrates how DT can be integrated into the WAAM manufacturing process. Utilizing NVIDIA Omniverse$^{TM}$, a DT model combining CAD, CAM, and CAE was developed, featuring data collection, remote collaboration, process monitoring, and data management capabilities. The DT serves as an integrated environment that bridges the physical and virtual worlds. Through the manufacturing of the Stanford Bunny, the study illustrates how DT assists in WAAM processes. It systematically collects and categorizes robotic arm motion parameters, point cloud data, and welding pool video recordings, all of which are well-tagged and stored in the cloud. This data provides essential support for subsequent CAE simulations and data-driven manufacturing. With the introduction of simulations and surrogate models, DT can establish a complete feedback control loop, which is crucial for achieving higher precision and reliability in WAAM. This DT framework lays the foundation for future optimization of the WAAM manufacturing process.

## 6. Acknowledgements

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