SynaCore

Scale Up

From Additive Manufacturing Digital Twin
to DT Enhanced Digital Passport
to Product Pre-Qualification

Defining the Technical Path for AM Industrialization

The Brain Analogy: Equipment Intelligence Evolution

↻ Begin with the end in mind

In this world, **every effect has its cause.** If one fails to understand the connection between cause and consequence, trouble ensues. Twelve years ago, I transitioned from traditional machining industry to additive manufacturing industry. Looking at the development trends of additive manufacturing from the perspective of how does mature industrialized production look like, I find that the patterns in the world are so full of cause and effect.

At that time, I contemplated an essential challenge with "black hole" characteristics that additive manufacturing would eventually face: our attempt to solve AM's **complexity** using traditional **trial-and-error methods**. This **mismatch** would cause enterprises **to suffocate as they grew larger**.

Back then, compared to the extreme OEE (Overall Equipment Effectiveness) achieved in the traditional machining industry has achieved, additive manufacturing remained in a stage lacking of the equipment "brains." And not only the "brains", taking metal 3D printing as an example, during the printing process, equipment still lacked "eyes," "ears," "nose," and other sensory systems.

The collaborative relationship between the human cerebrum and cerebellum is far more complex and bidirectional than the traditional "command-execution" understanding. The cerebellum serves as a "universal co-processor," dynamically coordinating neural oscillation phase differences across cortical regions to achieve cross-brain information integration. The cerebrum holds ultimate decision-making authority, determining "what to do" and "why." The cerebellum acts as a precision optimizer, ensuring **"how to do it" with maximum accuracy and efficiency**. Bidirectional communication between cerebrum and cerebellum enables adaptive learning, automating the transformation from novice to expert.

So how does the metal 3D printing achieve the stage of adaptive manufacturing? The answer is simple, the printer need the "brain" systems work just like the human brain, and in this whitepaper is going to expalin how **digital twin plus AI** are going to work as the "brain" for the 3d printing systems.

Digital twin does not merely simulate physical equipment, it constructs a "virtual process operating system" with infinite scalability, Only when manufacturing know-how achieves "scalable" evolution through standardization, codification, and verifiability in the virtual world, can real world additive manufacturing **break free from the bandwidth constraints of the "human operating system" and shatter the development curse where uncertainty grows with scale**. When management complexity no longer increases exponentially with scale, enterprises can concentrate resources on the truly decisive nodes that determine success or failure-such as continuous optimization of process packages-rather than squandering excessive time on procedural friction and internal inefficiencies.

This white paper aims to clarify this evolution, from which you will derive substantial benefits for long-term sustainable development.

XiaoYan (Kitty) Wang / CEO of SynaCore

OVERVIEW

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Executive Summary

The Three-layer Leap industrialization path

> **Core Thesis**
>
> Digital twin is not merely a technical tool but a **reusable, scalable, tradable strategic asset.** Enterprises first building the "Twin-Enhanced Passport-Pre-Certification" closed loop will establish "brain-region wisdom" and competitive barriers difficult for latecomers to surmount.

The Three-Layer Leap Industrialization Path

1 Digital Twin

Building real-time, high-fidelity virtual mirrors of physical manufacturing processes, enabling paradigm shift from "empirical trial-and-error" to "model-based prediction," thereby shortening process development cycles and improving yield rates.

→ From Trial-and-Error → Model-Based Prediction

2 DT-Enhanced DPP

Through digital twin-enhanced data reconstruction, establishing part-level lifecycle digital threads, achieving leap from "difficult to trace" to "single-piece genetic mapping," laying foundation for circular remanufacturing.

→ From Batch Traceability → Single-Piece Genetic Mapping

3 Pre-Qualification

A "Model-to-Qualify" system based on trusted digital twin models, enabling paradigm migration from "post-hoc inspection" (Test-to-Qualify) to "pre-event prediction," shaping more robust quality infrastructure.

→ From Post-Hoc Inspection → Pre-Event Prediction

Industry Inflection Point: AM stands at a critical transition from "prototyping tool" to "scalable production." The industry's core paradox: **infinite design freedom** versus **insufficient quality certainty**.

Industrial Dilemma—
The "Certainty Gap"
in AM Industrialization

Current diagnosis of additive manufacturing industrialization challenges

Current Diagnosis: Scaling Constrained by "Uncertainty"

🔷 Quality Black Box

Key physical processes—melt pool dynamics, thermal stress evolution, microstructure formation —occur within sealed chambers.

Final performance heavily depends on process engineers' personal experience , with large yield fluctuations.

⚠ New designs or materials restart trial-and-error cycles

🔷 High-Dimensional Parameters

Dozens of strongly coupled parameters including laser power, scanning strategy, and layer thickness create exponentially vast optimization spaces.

Current DOE (Design of Experiments) demands massive samples with poor extrapolation .

Parameter Space 10^{15+}

🔷 Data Silos

CAD design, process parameters, online monitoring, post-processing, and final inspection data reside in different systems.

Knowledge cannot accumulate or be reused ; each production nearly starts from zero.

- ⊗ CAD Design
- ⊗ Process Parameters
- ⊗ Online Monitoring
- ⊗ Final Inspection

📈 Break the bottleneck which hold the industrialization back

With geometric freedom and material efficiency, additive manufacturing has become revolutionary in aerospace, medical implants, and high-end molds. However, industrialization faces a fundamental "certainty gap" that constrains scalability.

Fundamental Contradiction:
Mismatch Between Traditional Trial-and-Error and AM Complexity

1 $ Cost Paradox

Validating process windows for complex parts requires multiple physical prints. Single metal prints cost thousands to tens of thousands of dollars , with no guarantee of finding global optima.

Average Validation Cost	$50K-200K-more
Success Rate	30-60%

2 🕐 Time Paradox

While AM offers flexibility, part process certification cycles are long, missing product launch windows. Traditional "manufacture-inspect-correct" logic hits fundamental limits.

Certification Cycle	6-18 months
Market Window	3-6 months

3 🧠 Knowledge Paradox

Critical process knowledge exists in personal experience, impossible to standardize or transfer, creating "brain drain, skill loss" risks.

AM's "Process-as-Product" Nature

Any microscopic process fluctuation accumulates into macroscopic performance variance. This fundamental characteristic makes traditional quality control approaches inadequate.

🔬 Microscopic Level
Melt pool instability, thermal gradient variations

↓

🔩 Macroscopic Impact
Porosity, warping, microstructure defects

💡 Strategic Imperative

Industrialization prerequisites are **controllable, reliable, predictable manufacturing.** This requires shifting quality control points to the design phase, establishing **"pre-event prediction"** capability—precisely the strategic value of digital twin technology.

The Brain Analogy: Equipment Intelligence Evolution

⚠ The "Black Hole" Challenge

The attempt to solve AM's **complexity** using traditional **trial-and-error** methods. This mismatch would cause enterprises to suffocate as they grew larger.

Key Insight: Just as the human brain consumes 20-25% of the body's energy, no one question how important the brain plus eyes, ears and nose are. Equipment brain is equally vital.

The Missing Senses

Compared to the exceptionally high Overall Equipment Effectiveness (OEE) achieved in conventional machining, additive manufacturing must evolve beyond the "brainless" era of equipment. Beyond simply possessing a "brain," metal 3D printing systems require effective monitoring and control capabilities that can truly collaborate with this intelligence.

👁 Eyes	🔄 Ears	🌬 Nose

Monitoring and Control

Sensor Classification by Technology Category

📷 Optical Camera

• Industrial camera
High-precision imaging for manufacturing quality control

• High speed photography
Ultra-fast frame rate capture for dynamic process analysis

• Spectrometer
Wavelength-based material composition analysis

• Contact Image Sensor
Direct-contact scanning for document and surface imaging

- Melt Pool Geometry Imaging
- Spatter and Plume Monitoring
- Geometric Feature Analysis

Key Applications:
Surface Defect Detection and Geometric Quality Inspection

🌡 Thermal Camera

• Infrared thermal imaging
Non-contact temperature measurement using IR radiation detection

• NIR Camera
Near-infrared imaging for enhanced visibility in low-light conditions

• LWIR Camera
Long-wave infrared detection for thermal signature analysis

- Melt pool thermal field monitoring
- In-situ Thermal Anomaly Detection
- Solidification Cooling Rate Analysis

Key Applications:
Porosity, Lack-of-Fusion, and Overheating Detection

🎤 Acoustic Sensor

• Acoustic emission
Stress wave detection for structural health monitoring

• Other passive transducers
Vibration and sound pressure measurement devices

- Acoustic Emission (AE) Signal Acquisition
- Spectral Analysis
- Internal Defect Detection

Key Applications:
Precursor Detection of Crack and Pore Formation

⋯ Others

• Eddy current
Conductive material inspection

• Synchrotron X-ray
High-resolution internal imaging

• Optical coherence tomography
Cross-sectional imaging

• Laser ultrasonics
Non-contact ultrasonic testing

SynaCore AM-DT Digital Twin

The Brain Analogy

AM-DT For Simulation

☁ VIRTUAL WORLD
Digital twin creates virtual replicas enabling simulation, prediction & optimization before physical production

💡 KEY INSIGHT
Digital twins enable **scalability** through virtual validation before physical production

⇄

🖥 PHYSICAL WORLD
Real-time production with sensor feedback enabling continuous optimization & quality assurance

Thermal history
Showing spikes as material is built

Porosity
Important for defect assessment

Distortion
Compared to original geometry

Microstructure
Grain shape and size in 3D

2 cm

Precipitates
Important for material strength

Mechanical properties
Key for part qualification
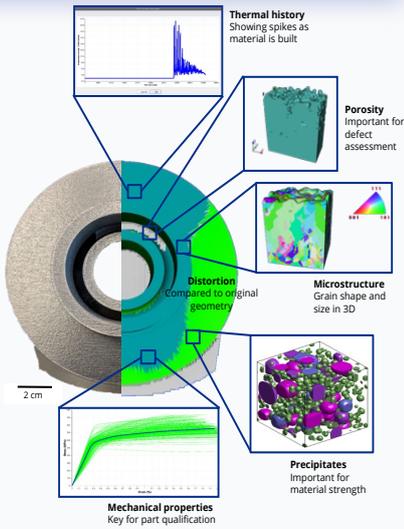
SynaCore AM-DT Digital Twin

↻ SynaCore Digital Twin for Simulation
One-Stop Self-Evolving Advantage

SynaCore's Digital Twin transcends traditional simulation by integrating **continuous learning capabilities** that automatically refine predictions based on real-world manufacturing feedback, eliminating the iterative manual calibration cycles.

Multi-Scale Ready	Memory Optimized	API Integration

3× Faster Iteration

Temperature (K)
4000
2767
1533
300

z
y
x

### ≋ End-to-End Prediction Pipeline
Multi-layer individual laser tracks to compute porosity, surface roughness, and microstructure

1 **Macro Deformation Prediction**
Warpage, shrinkage, and distortion analysis during printing

2 **Microstructure Evolution**
Grain growth, phase transformation, and solidification modeling

3 **Mechanical Property Forecasting**
Tensile strength, hardness prediction and else

Multi-phase thermal solver

Microstructure solver

Phase transition solver

Fluid dynamics solver
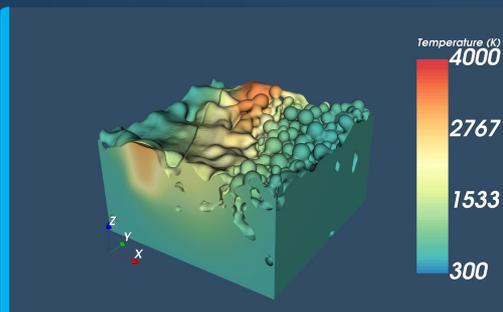
Key Differentiators

- ✓ Part Scale, site specific
- ✓ Close loop
- ✓ Multi-scale integration
- ✓ Embedded heat treatment prediction and optimization
- ✓ Embedded functions including Mesher, AI alloy, and Adaptive ToolPath
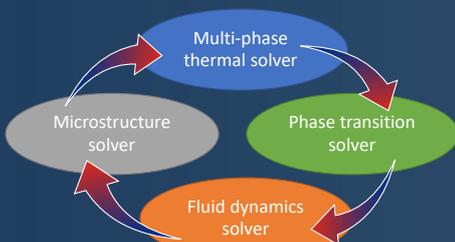
The Brain Analogy: SynaCore AM-DT digital twin
AM-DT Integrated Advance Mesher: Intelligent Mesh Generation Engine

Core Capabilities

Complex Geometry Handling
Automatic mesh generation for intricate CAD models with internal channels, lattice structures, and freeform surfaces

Adaptive Refinement
Dynamic mesh density adjustment based on stress concentration, thermal gradient, and geometric complexity

Computational Efficiency
Optimized mesh topology that balances accuracy with solver performance, reducing computation time

SynaCore Mesher
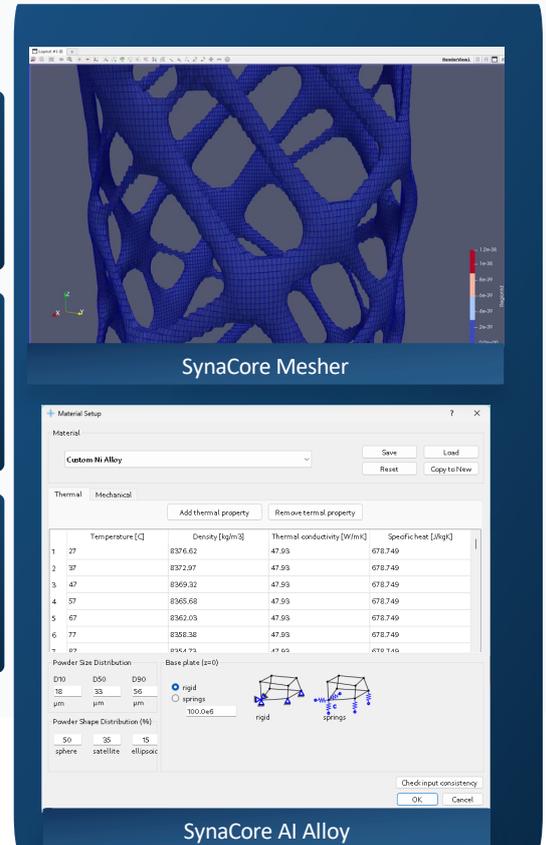
SynaCore AI Alloy

The Brain Analogy: SynaCore AM-DT digital twin
AM-DT Integrated AI Alloy

Disrupting Traditional Experience-Based Development

SynaCore's **AI Alloy** module fundamentally transforms alloy design by replacing decades of trial-and-error experimentation with AI-driven computational materials science. The system leverages artificial intelligent to predict composition-property relationships with unprecedented accuracy.

Traditional Approach
- ✗ years development cycle
- ✗ Expert-dependent decisions
- ✗ High experimental cost
- ✗ Limited exploration space

AI Alloy Approach
- ✔ Shortened development
- ✔ Data-driven optimization
- ✔ Significant cost reduction
- ✔ Full composition space

The Brain Analogy: SynaCore AM-DT digital twin
AM-DT Integrated *Adaptive ToolPath*

🌡 Thermal History-Driven Strategy

SynaCore's **Adaptive ToolPath** technology generates intelligent machining strategies by analyzing **thermal segments** during the manufacturing process. The system dynamically adjusts tool paths based on accumulated heat distribution, **reducing cracking, preventing deformation, and avoiding other defects**.

🌡 Thermal Monitoring
Continuous temperature field calculation and heat accumulation tracking

Dynamic Path Adjustment
Adaptive tool path modification based on thermal gradients

🛡 Thermal Damage Prevention
Automatic cooling pauses and speed adjustments to prevent overheating

Built-in Digital Twin Integration

Adaptive ToolPath seamlessly integrates with SynaCore's Digital Twin platform, enabling **close loop feedback** between predicted and actual performance.

🔬 SynaCore Built-in Adaptative Toolpath

1 **Composition Optimization**
Multi-objective optimization balancing strength, ductility, and cost

2 **Property Prediction**
Mechanical property forecasting

3 **Phase Diagram Prediction**
Thermodynamic stability and phase transformation modeling

4 **Process Parameter Link**
Integrated AM process window optimization

Technical Architecture— The "Three-Layer Leap" Industrialization Path

AM industrialization is quality infrastructure reconstruction through three-layer progressive architecture

Layer One
Base State: Additive Manufacturing Digital Twin (AM-DT)

Key Differentiators of Additive Manufacturing Digital Twin AM-DT

🕐 Time Characteristic	Interpret multi mode sensor's data, continuous improving prediction accuracy
⇄ Data Flow	Bidirectional closed loop (physical ↔ virtual)
🔗 Physical Connection	Continuous synchronization via sensors
📈 Evolution Capability	Self-updating with physical entity state
💎 Value Positioning	Asset (value appreciation)

Three Technical Layers of AM-DT

1 Mechanism Kernel Based on Multi-Physics Simulation
Ultra-high-precision multi-physics simulations (CFD, thermodynamics, solid mechanics) predicting temperature fields, stress-strain fields, defect formation —equipping every operation with a "prospective perspective lens."

2 Adaptive Parameter Optimization
Refer to Chapter 3.3

3 Closed-Loop Feedback and Model Self-Evolution
Integrating real-time sensing data for "continually optimizing." Deviations captured and used to dynamically correct models, enabling continuous evolution.

⚠️

Critical Distinction

Unlike process monitoring visualization, AM digital twins must handle **dynamically evolving physical entities**—parts growing layer by layer, second by second in geometry, thermal state, and material properties.

Layer Two
Intermediate State:
Digital Twin-Enhanced Product Digital Passport (DT-Enhanced DPP)

AM "Digital Passport" Essence

Part final performance related with digital definitions—including 3D models, process parameters, scanning paths, material information constituting the "digital thread."

Traditional quality traceability systems only trace to "batch" level, unable to locate "every laser melt pool, every layer printing trajectory."

Regulatory Imperative: EU ESPR 2027

The EU's Sustainable Products Initiative (ESPR) has clarified: **by 2027, key industrial products must carry Digital Product Passports (DPP).**

- ✓ **Full Lifecycle Compliance:** Meeting international environmental and data disclosure regulations
- ✓ **Rapid Defect Localization:** Upgrading from "batch recall" to "single-piece traceability"
- ✓ **Carbon Footprint Transparency:** Quantifying and optimizing environmental benefits
- ✓ **Data Sovereignty:** Achieving international circulation while protecting core enterprise data

Core Upgrade: "DT-Enhanced" Product Digital Passport

The core upgrade lies in **embedding digital twin predictive data as inherent passport components:**

Technical Implementation

Direct part marking embeds unique identifiers (data matrix codes or QR codes) into part entities, linking to digital twin-enhanced passports.

⊞ Users scan the part to access the authorized "digital genetic blueprint" permitted for disclosure.

Passport Data Components

- · 3D model and design specifications
- · Complete process parameters and scanning paths
- · Real-time monitoring data during printing
- · Post-processing and inspection records
- · Material batch and supplier information...

DT-Enhanced Passport Data Components

+ Digital twin predictive performance data

Layer Three
Ultimate State: Standard-Embedded Product Pre-Qualification

Future Qualification Transformation

Manufacturers submit to regulators or customers **not merely limited physical test reports but high-confidence digital twin models** supporting part manufacturing and their historical prediction accuracy proofs.

By reviewing digital twin completeness and accuracy, combined with partial physical validation, **rapid and low-cost "pre-qualification" for** mass production as key references becomes possible.

Pre-Qualification vs. Physical Qualification: Dialectical Unity

✳ Traditional Qualification

· Legal effectiveness confirmation

· Dependent on physical testing

· Sampling inspection

· Mandatory and final

🏅 Pre-Qualification

· Process performance prediction

· Based on models and data

· Full-population coverage

· Flexible and forward-looking

Future Development Trends

1 Initial Phase

Pre-qualification as auxiliary tool for design optimization and risk screening

↓

2 Mid Phase

Pre-qualification conclusions conditionally accepted by regulators in specific scenarios

↓

3 Long-term

Formation of "simulation-first, test-validation" new processes

🤝

Together they form "prediction + confirmation" dual-track quality assurance. Pre-qualification shortens qualification cycles; qualification endows pre-qualification with social credibility.

Core Mechanisms

⚙ **Design Phase Standard Compliance:** Automatic verification against material specs, geometric tolerances, NDT criteria

✅ **A Priori Certification:** Virtual testing before print jobs, verifying predicted performance meets requirements

☁ **Pre-Qualification-as-a-Service:** Digital twins as "certifiable agents" with queryable confidence intervals

Why Should Digital Twins Be Accounted as Assets Rather Than Expenses?

Five dimensions supporting the strategic asset classification of digital twin software

♟ Strategic Premium

Unpredictability → Designability

AM suffers from high print failure rates and narrow process windows. Digital twins advance defect resolution to "virtual printing" stage, converting "sunk costs" into "premium profits."

Success Rate Improvement

⚑ Asset Leverage

Equipment Depreciation → Digital Appreciation

Through real-time optimization, twins can elevate OEE from 40-55% to above 70% , continuously improving with data accumulation—equivalent to increasing capacity "without new equipment."

Constantly Increasing OEE

◷ Time Leverage

Linear Development → Parallel Development

Digital twins enable design, process, supply chain, and maintenance to iterate in parallel on the same virtual model, shortening design cycles and accelerating time-to-market.

Cycle Time Reduction

◐ Knowledge Leverage

Personal Experience → Enterprise Assets

Process parameters, defect libraries, and compensation algorithms encapsulated into twin models form reusable, tradable "digital intellectual property."

Replication Potential

🛡 Risk Hedging

Uncertain Costs → Calculable Premiums

Digital twins enable "scenario simulation" for supply chain, quality, and maintenance, transforming unpredictable risks into manageable, calculable premiums.

Decrease Risk Exposure

Fundamental Reason

Digital twin software upgrades **"post-hoc remediation"** production models to **"pre-event victory"** competitive modes, continuously amplifying marginal returns over year by year.

Conclusion

Let us jointly welcome the new era of intelligent manufacturing

Toward a Future
"Born Digital, Proven by Prediction,Realized in Physical"

Every part traceable, every manufacturing predictable, every product pre-"health checked"

Additive manufacturing industrialization is essentially **transforming uncertainty into calculable risk.**

Digital Twins
Provide the capability to **predict physical reality**

Enhanced Passports
Solidify predictions into **traceable digital assets**

Pre-Qualification
Quality infrastructure on **trusted predictions**

This is not merely technical upgrade but **fundamental transformation of quality philosophy**—from "post-hoc remediation" to "pre-event victory," from "empirical art" to "data science," from "physical verification" to "digital trust."

Appendix: Glossary

- AM: Additive Manufacturing
- DPP: Digital Product Passport
- P-S-P: Process-Structure-Property
- OEE: Overall Equipment Effectiveness
- Model-to-Qualify: Model-based qualification, distinct from traditional Test-to-Qualify

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