

6D Printing Technology: Integration of Multi-Axis Motion and Smart Materials for Intelligent Manufacturing

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Abstract— The rapid evolution of Additive Manufacturing (AM) has transformed conventional three-dimensional (3D) fabrication into intelligent, adaptive, and multi-functional manufacturing systems. While 4D printing introduced time-dependent shape transformation through smart materials, its adoption remains constrained by limited mechanical strength, restricted geometric flexibility, and inadequate multi-axis fabrication capability. To address these limitations, recent research has shifted toward integrating the structural advantages of five-axis (5D) printing with the stimuli-responsive characteristics of 4D printing, giving rise to 6D printing as a next-generation intelligent manufacturing paradigm. This paper presents a systematic, PRISMA-guided literature review of 85 peer-reviewed studies selected from an initial pool of 850 records retrieved from major scientific databases. The review examines the evolution of additive manufacturing from 3D to 6D printing, with emphasis on multi-axis toolpath generation, smart material integration, computational modelling, and intelligent manufacturing strategies. Particular attention is given to smart material databases, the coupling of Molecular Dynamics (MD) and the Finite Element Method (FEM) for multi-scale material modelling, and the role of artificial intelligence (AI) in process optimization and material behaviour prediction. The review synthesizes recent developments through comparative technology analysis, publication-trend assessment, and identification of key research gaps, including the absence of standardized design methodologies, limited digital twin integration, insufficient material characterization databases, and challenges associated with industrial-scale implementation. The findings indicate that 6D printing has the potential to improve structural integrity, functional adaptability, manufacturing efficiency, and material utilization relative to existing additive manufacturing approaches. This review proposes a conceptual 6D Printing Framework (6DPF) intended to guide future research toward AI-enabled, sustainable, cyber-physical manufacturing for biomedical engineering, aerospace, architecture, engineering and construction (AEC), soft robotics, and smart infrastructure applications.

Keywords— Additive manufacturing; 6D printing; 5D printing; 4D printing; smart materials; multi-axis manufacturing; molecular dynamics; finite element method; PRISMA; artificial intelligence; digital twin; intelligent manufacturing.

I. INTRODUCTION

Additive Manufacturing (AM), commonly referred to as three-dimensional (3D) printing, has transformed modern

manufacturing by enabling the layer-by-layer fabrication of complex geometries directly from digital models. Compared with conventional subtractive manufacturing, AM offers reduced material wastage, design flexibility, rapid prototyping, mass customization, and shortened product development cycles [9,10,11], advantages that have accelerated its adoption across aerospace, biomedical engineering, automotive manufacturing, architecture, engineering and construction (AEC), robotics, and energy sectors. Nevertheless, conventional 3D printing remains constrained by anisotropic mechanical properties, poor interlayer bonding, staircase effects on curved surfaces, extensive support-structure requirements, and restricted post-fabrication adaptability [12,13,14]. These limitations restrict the production of high-performance functional components, particularly where structural reliability and intelligent functionality are required.

To address these limitations, additive manufacturing has evolved toward intelligent manufacturing systems. The introduction of 4D printing incorporated smart materials capable of responding to external stimuli such as temperature, moisture, light, magnetic fields, and electrical signals, enabling printed structures to transform their geometry or functionality over time [5,6,7,8]. While 4D printing expanded the functional capability of additive manufacturing, practical implementation remains constrained by relatively low mechanical strength, limited material availability, slow response characteristics, and challenges associated with large-scale manufacturing.

Subsequently, 5D printing emerged by replacing conventional three-axis Cartesian motion with synchronized five-axis movement [15,16]. Rather than planar layer-by-layer deposition, 5D printing deposits material along curved toolpaths that follow component geometry, improving load distribution, reducing stress concentration, minimizing support material, and enhancing structural strength while maintaining material efficiency [17,18]. However, 5D printing focuses primarily on structural optimization and lacks the adaptive behaviour introduced by smart materials.

Recent advances in intelligent manufacturing have motivated the development of 6D printing, which integrates the structural advantages of five-axis additive manufacturing with the stimuli-responsive capabilities of 4D printing [1,2,4]. Beyond simply combining these technologies, 6D printing represents a cyber-physical manufacturing paradigm incorporating smart materials, computational intelligence, artificial intelligence, digital twins, and multi-scale computational modelling to produce intelligent structures capable of autonomous adaptation and enhanced functional performance.

Despite growing research interest in intelligent additive manufacturing, the available literature remains fragmented: most studies address 4D printing, 5D printing, smart materials, computational modelling, or multi-axis toolpath optimization independently, with relatively few attempts to integrate these developments into a unified framework for 6D printing [1,2,3,4]. Challenges related to standardized design methodologies, smart material databases, AI-assisted process optimization, multi-scale material modelling, digital twin integration, and industrial scalability remain largely unresolved.

To address these gaps, this review presents a systematic, PRISMA-based assessment of recent advances in additive manufacturing, emphasizing the transition from conventional 3D printing toward intelligent 6D printing systems. Section 2 describes the review methodology and publication-trend analysis. Section 3 traces the technological evolution from 3D to 6D printing and identifies critical research gaps. Section 4 presents the proposed 6D Printing Framework (6DPF), covering the smart material database, multi-scale computational modelling, and multi-axis toolpath optimization. Section

5 discusses current challenges, Section 6 discusses industrial perspectives, Section 7 presents results and discussion, Section 8 outlines future work, and Section 9 concludes the review.

Multi-Scale Modeling and Analysis of SMs

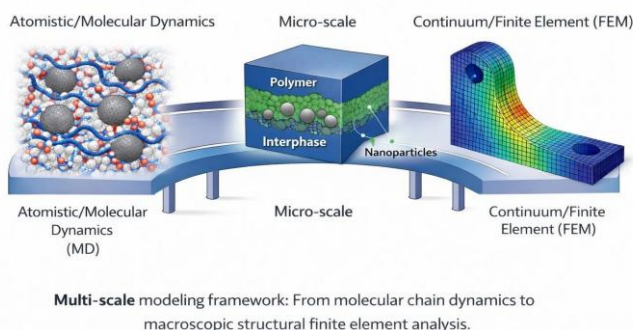


Figure 1. Conceptual multi-scale framework of the proposed 6D Printing Framework (6DPF), illustrating the integration of smart material databases, molecular dynamics (MD), finite element method (FEM), multi-axis toolpath planning, and artificial intelligence for intelligent additive manufacturing.

II. MATERIALS AND METHODS

A. Review Methodology (PRISMA Approach)

To ensure a comprehensive, transparent, and reproducible assessment of the current state of research in intelligent additive manufacturing, this review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines. The PRISMA framework provides a structured methodology for identifying, screening, selecting, and synthesizing relevant literature while minimizing selection bias and improving reliability.

A systematic literature search was performed across Scopus, Web of Science, IEEE Xplore, and ScienceDirect, owing to their extensive coverage of peer-reviewed research in additive manufacturing, materials science, mechanical engineering, and computational modelling. The search strategy used Boolean operators combined with keywords related to the evolution of additive manufacturing technologies, including “6D Printing,” “5D Printing,” “4D Printing,” “Multi-axis Additive Manufacturing,” “Smart Materials,” “Shape Memory Polymers,” “Multi-scale Modelling,” “Molecular Dynamics,” “Finite Element Method,” “Digital Twin,” “Artificial Intelligence,” and “Structural Optimization.” Multiple search-term combinations were used to maximize retrieval while including interdisciplinary studies relevant to intelligent manufacturing.

The initial database search identified 850 publications indexed between 2015 and 2024 (Scopus, $n = 340$; Web of Science, $n = 250$; IEEE Xplore, $n = 150$; ScienceDirect, $n = 90$; other sources, $n = 20$). Following the PRISMA workflow, 145 records were removed before screening (120 duplicates, 20 excluded by automation tools, 5 removed for other reasons), leaving 705 records for title/abstract screening. Of these, 520 were excluded as not relevant, leaving 185 reports sought for retrieval; 15 could not be retrieved, leaving 170 reports assessed for eligibility against predefined inclusion and exclusion criteria.

Inclusion criteria comprised peer-reviewed journal articles, review papers, and high-quality conference proceedings addressing 4D printing, 5D printing, 6D printing, smart materials, multi-axis additive manufacturing, computational modelling, structural optimization, or intelligent manufacturing systems, published in English with substantive theoretical, computational, or experimental contributions. Publications addressing only conventional three-axis additive manufacturing without discussion of intelligent manufacturing concepts were excluded, as were editorials, patents, theses, book chapters, duplicate records, and studies lacking sufficient technical detail. At the eligibility stage, 85 reports were excluded (not relevant to the research question, $n = 50$; insufficient data, $n = 20$; wrong study design, $n = 10$; not in English, $n = 3$; other reasons, $n = 2$), leaving 85 core publications selected for qualitative synthesis. The complete selection process is shown in Figure 2.

B. Publication Trend Analysis

Figure 3 illustrates the year-over-year evolution of publications in advanced additive manufacturing from 2015 to 2024, highlighting the transition from independent investigations of 4D and 5D printing toward the emerging concept of 6D printing. During 2015–2017, research activity concentrated on 4D printing, with studies focusing on Shape

Memory Polymers (SMPs), hydrogels, and stimuli-responsive composites capable of controlled shape transformation [6,7,8]; research on multi-axis manufacturing remained in its early stages.

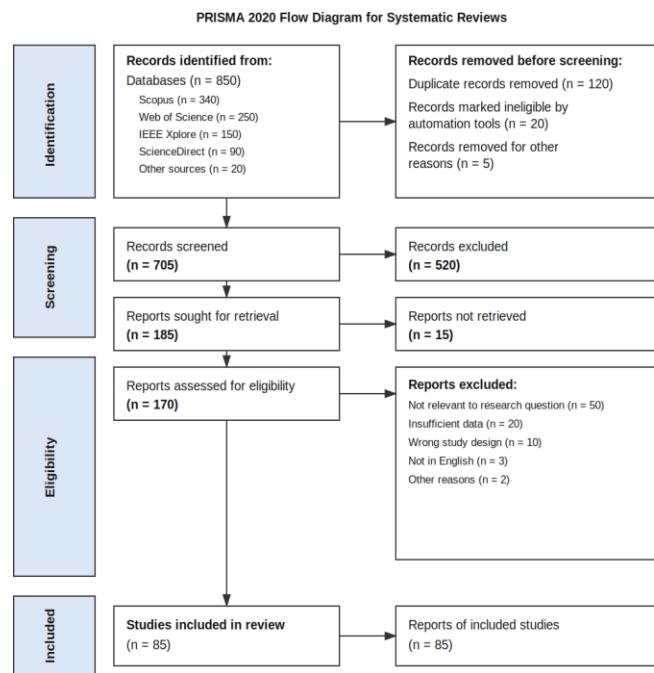


Figure 2. PRISMA 2020 flow diagram (identification, screening, eligibility, included), reconciled with the reported total of 85 included studies.

Figure 2. PRISMA 2020 flow diagram (identification, screening, eligibility, included), reconciled with the reported total of 85 included studies.

Between 2018 and 2020, publication activity increased with the emergence of 5D printing, as researchers explored synchronized five-axis toolpath generation for curved deposition paths, improved structural integrity, reduced support-material requirements, and enhanced mechanical performance [16,17,18], alongside advances in computational toolpath optimization, finite element analysis, and topology optimization.

A substantial increase in publications is observed after 2020, coinciding with the rapid adoption of Industry 4.0 technologies, artificial intelligence, digital manufacturing, and cyber-physical production systems [26,27]. These multidisciplinary efforts laid the foundation for 6D printing, which combines the geometric flexibility of 5D printing with the adaptive functionality of 4D printing. Although 4D printing remains the most mature research area, 5D printing has grown steadily due to its structural-optimization advantages, while 6D printing — though comparatively small in publication volume — exhibits the highest annual growth rate, indicating rising research interest in intelligent, adaptive manufacturing capable

of integrating smart materials, multi-axis motion, AI, digital twins, and multi-scale computational modelling.

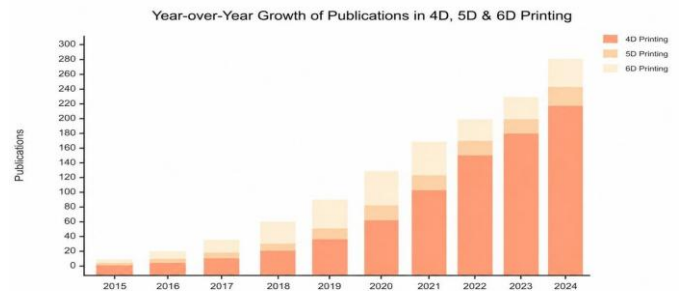


Figure 3. Year-over-year growth of publications related to 4D, 5D, and 6D printing between 2015 and 2024, illustrating the evolution of research interest in intelligent additive manufacturing technologies.

III. EVOLUTION OF ADDITIVE MANUFACTURING: 3D TO 6D

The field of Additive Manufacturing has undergone a remarkable transformation over the past decade, evolving from conventional three-dimensional (3D) printing to intelligent, adaptive, and data-driven manufacturing systems. Each technological generation was developed to overcome the limitations of its predecessor while expanding the functional capabilities of additive manufacturing, reflecting the growing demand for components with enhanced structural performance, adaptive functionality, improved material efficiency, and greater manufacturing flexibility.

The first generation, 3D printing, enabled layer-by-layer fabrication directly from digital models and significantly reduced material waste relative to subtractive manufacturing, but remains constrained by anisotropic mechanical properties, poor interlayer bonding, staircase effects, high dependence on support structures, and limited post-fabrication functionality [9,10,13].

4D printing extended conventional 3D printing through smart materials capable of responding to external stimuli such as temperature, moisture, light, magnetic fields, and electrical signals. Shape Memory Polymers (SMPs), hydrogels, and other stimuli-responsive materials enabled printed components to undergo controlled shape transformation after fabrication [6,7,19,20], expanding applications in soft robotics, biomedical implants, drug delivery, and self-deploying structures. Nevertheless, low mechanical strength, limited material availability, and slow response remain major adoption barriers [5,8].

5D printing replaced conventional three-axis motion with synchronized five-axis manufacturing, following curved toolpaths that conform to component geometry. This improves filament alignment along principal stress trajectories, enhancing structural integrity, reducing stress concentration, lowering support-material consumption, and improving load-bearing capacity [15,16,17], making it attractive for aerospace components, pressure vessels, and biomedical implants. However, 5D printing focuses on geometric optimization and does not inherently provide adaptive or programmable functionality [18].

6D printing represents the convergence of multi-axis manufacturing, smart materials, computational intelligence, and advanced digital technologies. It integrates the structural advantages of 5D printing with the adaptive capabilities of 4D printing while incorporating AI, digital twins, multi-scale computational modelling, and real-time process optimization [1,2,4], enabling structures capable of autonomous adaptation, predictive performance assessment, and optimized resource utilization. Table 1 summarizes the key differences among the four generations.

TABLE 1. Comparative analysis of the technological evolution from 3D to 6D printing, highlighting differences in manufacturing principles, material systems, structural performance, intelligent capabilities, and industrial applications.

Feature	3D Printing	4D Printing	5D Printing	6D Printing
Manufacturing principle	Layer-by-layer planar deposition (X–Y–Z)	3D printing + stimuli-responsive materials	Five-axis non-planar curved-layer deposition	Five-axis manufacturing + smart materials + AI
Motion axes	Three (X, Y, Z)	Three (X, Y, Z)	Five (X, Y, Z + two rotational)	Five-axis with adaptive, AI-driven control
Primary materials	PLA, ABS, PETG, nylon, metals, ceramics	SMPs, hydrogels, SMAs, smart composites	High-strength polymers, carbon-fibre composites, metal alloys	Smart nanocomposites, metamaterials, programmable materials
Shape adaptability	None	High	None	Very high
Feature	3D Printing	4D Printing	5D Printing	6D Printing
Mechanical strength	Moderate	Moderate	High	Very high
Support-material need	High	High	Low	Very low
AI integration	Not typical	Limited	Limited	Extensive
Digital twin integration	Not available	Rarely implemented	Emerging	Fully compatible
Major applications	Rapid prototyping, tooling	Soft robotics, biomedical devices	Aerospace, orthopaedic implants	Intelligent infrastructure, adaptive aerospace/biomedical systems
Major limitations	Weak interlayer bonding, staircase effect	Limited material availability, low strength	High equipment complexity, expensive hardware	Lack of standard protocols, high implementation cost

A. Critical Research Gaps

Despite substantial progress in multi-axis manufacturing, smart materials, computational modelling, and intelligent process optimization, the transition from conventional 3D printing to intelligent 6D printing remains at an early stage. A critical analysis of the reviewed studies identifies six major research gaps.

1. Lack of unified multi-scale simulation frameworks. Existing CAD/CAM systems are developed primarily for conventional three-axis additive manufacturing and treat multi-axis toolpath planning, material behaviour, thermal analysis, and structural performance as separate processes

- [31,33], preventing simultaneous coupling of MD, FEM, thermal analysis, and multi-axis motion planning.
2. Smart material–kinematic compatibility. The behaviour of SMPs, SMAs, hydrogels, and other smart materials during multi-axis deposition remains insufficiently understood; continuous nozzle rotation and variable deposition orientation alter cooling rates, crystallization behaviour, residual stresses, and interlayer bonding, which may reduce responsiveness and durability [19,20].
3. Artificial intelligence and closed-loop manufacturing. Most existing systems rely on predefined toolpaths generated before fabrication; real-time process monitoring, adaptive parameter optimization, defect prediction, and autonomous decision-making remain limited [28,29,30].
4. Digital twin integration and real-time monitoring. Most existing studies employ offline simulation rather than real-time synchronization between physical manufacturing systems and their virtual counterparts [23,24,25], restricting predictive maintenance and lifecycle monitoring.
5. Industrial scalability and standardization. Most reported 6D printing demonstrations are laboratory-scale prototypes; scaling to aerospace, construction, and biomedical applications introduces challenges in calibration, repeatability, and cost, and internationally accepted standards are still lacking.
6. Sustainable manufacturing and material databases. Comprehensive sustainability assessments (lifecycle analysis, recyclability, energy consumption) for intelligent 6D printing remain scarce [40,41], and no standardized database of thermo-mechanical, electrical, and stimuli-responsive smart-material properties currently exists.

Addressing these gaps requires an integrated framework combining multi-axis manufacturing, smart materials, artificial intelligence, digital twin technology, and multi-scale computational modelling, summarized in Table 2.

TABLE 2. Summary of the critical research gaps, current limitations, and future research directions in the development of intelligent 6D printing technologies.

Research Gap	Current Limitation	Future Research Direction
Unified simulation framework	Separate CAD/CAM, FEM, and material models	Integrated MD–FEM–AI simulation platform
Smart material compatibility	Thermal degradation, inconsistent material response	Standardized processing parameters and smart-material databases
AI-assisted manufacturing	Limited real-time monitoring and adaptive control	Closed-loop AI-driven manufacturing systems
Digital twin integration	Offline simulation, limited process synchronization	Real-time digital-twin-enabled intelligent manufacturing
Industrial scalability	Laboratory-scale validation, lack of standardization	Industrial-scale validation and international manufacturing standards
Sustainability	Limited lifecycle assessment and environmental evaluation	Sustainable smart materials and circular manufacturing strategies

IV. THE PROPOSED 6D PRINTING FRAMEWORK (6DPF)

The proposed 6DPF is a conceptual intelligent manufacturing architecture integrating multi-axis additive

manufacturing, smart materials, computational modelling, and data-driven decision support. It is derived from systematic analysis of the 85 reviewed studies and synthesizes recent advances in 5D printing, 4D printing, artificial intelligence, digital twin technology, MD, and FEM into a generalized

computational architecture, rather than a new hardware platform, illustrating how these technologies can operate collaboratively to achieve intelligent, adaptive, and sustainable manufacturing.

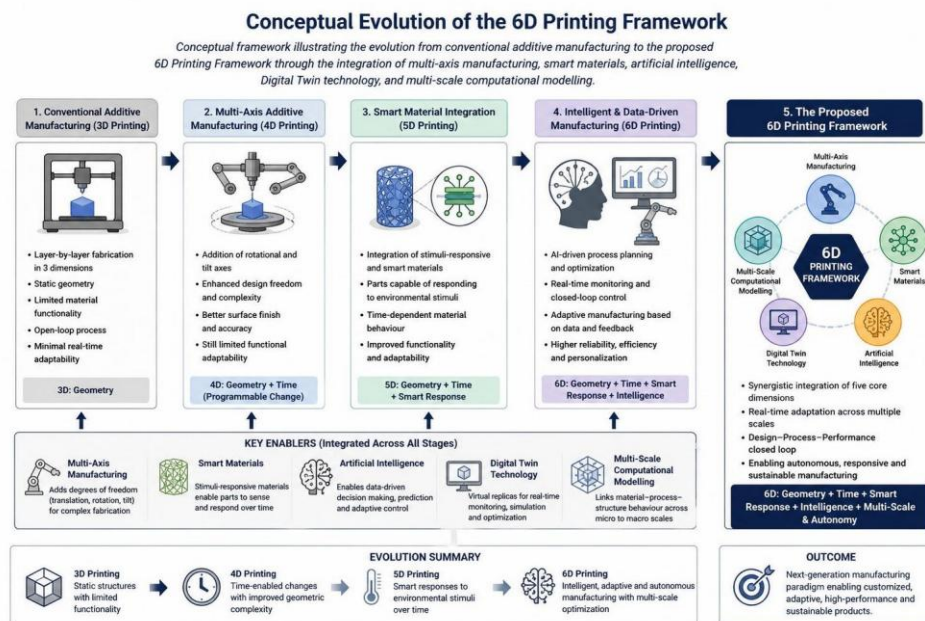


Figure 4. Conceptual framework illustrating the evolution from conventional additive manufacturing to the proposed 6D Printing Framework through the integration of multi-axis manufacturing, smart materials, artificial intelligence, digital twin technology, and multi-scale computational modelling.

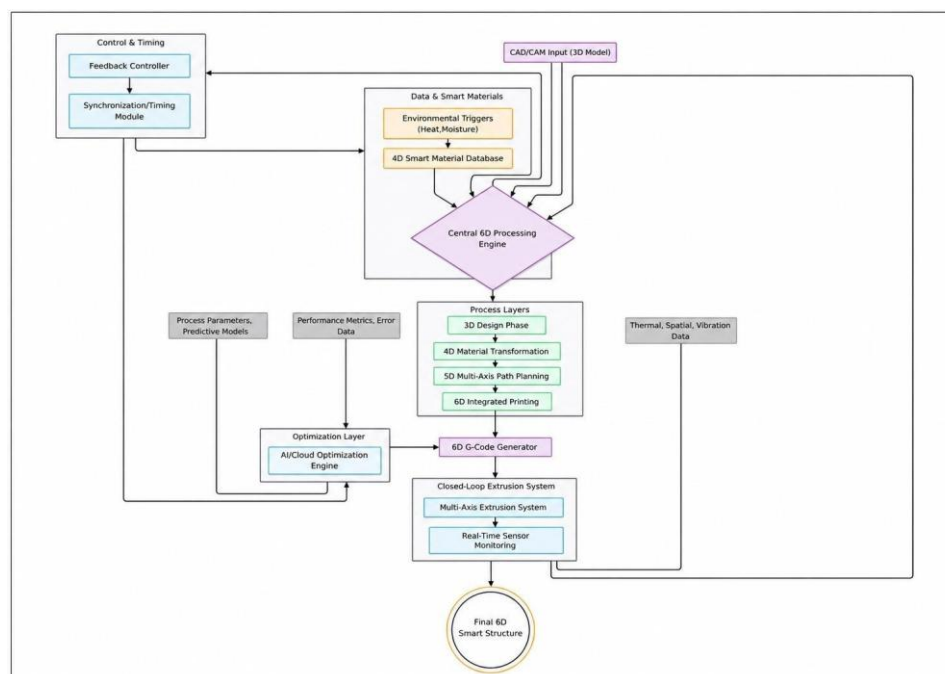


Figure 5. Comprehensive system architecture of the proposed 6D Printing Framework (6DPF), illustrating the integration of CAD/CAM design, multi-axis (5D) toolpath generation, smart material database, molecular dynamics (MD), finite element method (FEM), AI-based process optimization, digital-twin-enabled monitoring, and a closed-loop extrusion system.

The methodology follows a modular, hierarchical architecture in which each functional component performs a specialized task while continuously exchanging information

with the other modules through a closed-loop communication system. The workflow begins with digital product design (CAD/CAM), followed by geometric preprocessing and

multi-axis toolpath generation. A smart material database concurrently supplies thermo-mechanical, stimuli-responsive, and processing characteristics for intelligent material selection. Multi-scale computational modelling

— combining MD for material-level behaviour and FEM for structural performance prediction — evaluates mechanical integrity prior to fabrication, while AI algorithms optimize printing parameters, predict defects, and support adaptive decision-making throughout manufacturing.

A closed-loop monitoring and feedback mechanism continuously acquires process data (extrusion temperature, nozzle orientation, deposition quality, layer adhesion, material behaviour, geometric accuracy) from embedded sensors. AI-assisted algorithms analyse this data to enable real-time process optimization, predictive quality assessment, and adaptive parameter adjustment, improving accuracy, reducing waste, and enhancing production efficiency. The complete operational workflow is shown in Figure 5.

A. Database of Smart Materials — Stimuli Interaction Mechanisms

Smart Materials (SMs) are a fundamental enabling technology for intelligent 6D printing, providing the adaptive functionality that distinguishes it from conventional fabrication. Unlike traditional engineering materials, SMs can alter their shape, mechanical properties, or functional behaviour

in response to external stimuli — temperature, moisture, electric fields, magnetic fields, light intensity, pH, and mechanical loading [19,20,21,22] — forming the basis of programmable, time-dependent transformation in 4D printing.

Realizing 6D printing requires integrating these adaptive properties with the structural advantages of five-axis additive manufacturing. Recent studies indicate that smart-material behaviour is influenced not only by intrinsic thermo-mechanical properties but also by printing orientation, layer architecture, thermal history, cooling rate, and deposition trajectory, which significantly affect shape recovery, structural stability, response time, fatigue resistance, and long-term functional performance.

Shape Memory Polymers (SMPs), Shape Memory Alloys (SMAs), hydrogels, liquid crystal elastomers (LCEs), electroactive polymers (EAPs), magneto-responsive composites, and photo-responsive polymers represent the most extensively investigated smart-material families for intelligent additive manufacturing [19,20,21,22]. Recent research emphasizes establishing a standardized smart-material database integrating thermo-mechanical, chemical, electrical, magnetic, and stimuli-responsive properties into a unified computational framework to support AI-assisted material selection and, when coupled with MD/FEM simulation, multi-scale prediction of material performance before fabrication.

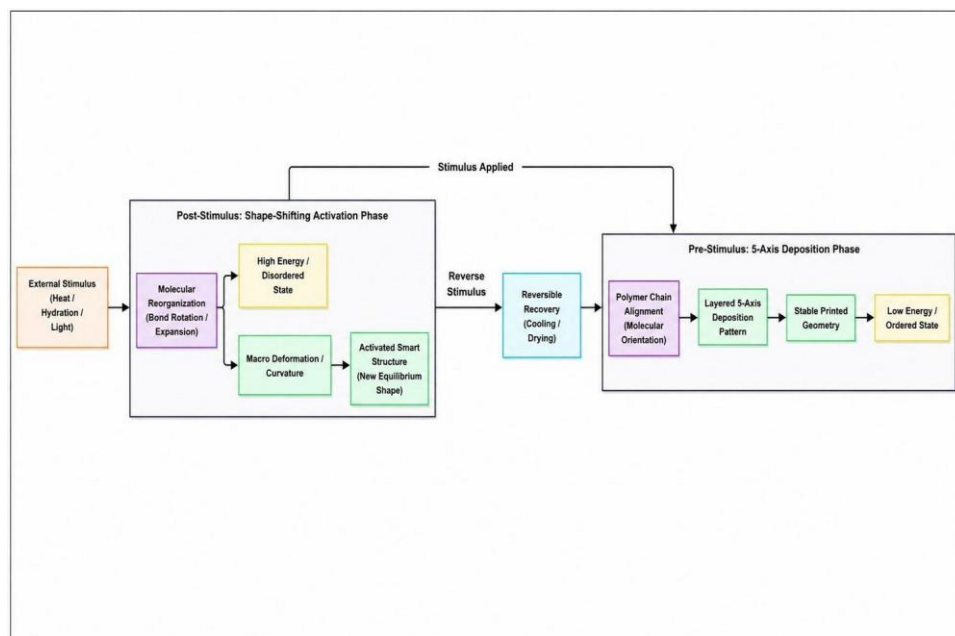


Figure 6. Schematic representation of smart polymer behaviour during the proposed 6D printing process, illustrating molecular alignment during five-axis curved-layer deposition and the subsequent stimuli-induced shape transformation activated by thermal, moisture, electrical, magnetic, or optical stimuli.

TABLE 3. Comparison of smart materials used in intelligent additive manufacturing based on their activation stimuli, mechanical properties, and typical applications.

Smart Material	Stimulus	Shape Recovery	Mechanical Strength	Typical Applications
Shape Memory Polymer (SMP)	Temperature	High	Moderate	Biomedical devices, soft robotics
Shape Memory Alloy (SMA)	Temperature	Very high	High	Aerospace actuators, adaptive structures
Hydrogel	Moisture / pH	High	Low	Drug delivery, tissue engineering
Electroactive Polymer (EAP)	Electric field	High	Moderate	Artificial muscles, sensors
Liquid Crystal Elastomer (LCE)	Heat / light	High	Moderate	Soft robotics, adaptive optics
Magneto-responsive Composite	Magnetic field	Moderate	High	Intelligent actuators, aerospace systems

B. Multi-Scale Modelling and Analysis of Smart Materials and Structures

The functionality of 6D-printed components depends on the complex interaction between smart materials, multi-axis deposition strategies, and external stimuli, requiring a multi-scale modelling framework capturing phenomena from the molecular to the structural level. During layer-by-layer deposition, polymeric matrices — often reinforced with nanoparticles or functional fillers

--undergo simultaneous melting, extrusion, cooling, and solidification, so final mechanical behaviour is strongly influenced by molecular chain orientation, crystallization, interlayer bonding, residual stresses, and reinforcement distribution.

At the molecular scale, Molecular Dynamics (MD) simulations provide insight into polymer chain mobility,

intermolecular interactions, nanoparticle dispersion, glass transition, and stimuli-responsive behaviour [31,33], supplying material parameters not obtainable from continuum models alone. At the structural scale, the Finite Element Method (FEM) predicts stress distribution, deformation, failure mechanisms, thermal behaviour, vibration characteristics, and structural stability, and supports optimization of filament orientation and toolpath planning for curved-layer, five-axis deposition [32,34].

The coupling of MD and FEM establishes a multi-scale computational framework in which molecular-level properties are transferred to continuum-scale structural simulations, improving prediction accuracy while reducing dependence on costly experimental trials. Coupling multi-scale simulation with AI and digital twin technology further enables continuous model updating using real-time manufacturing data, improving defect detection and adaptive process optimization [24,25,28].

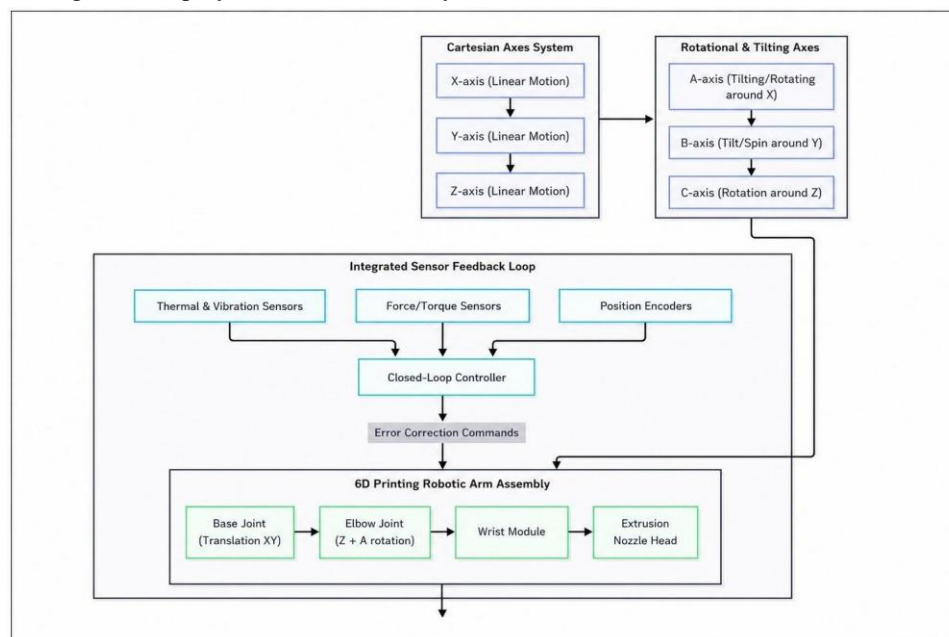


Figure 7. Kinematic architecture of the proposed 6D printing system illustrating the coordinated motion of the Cartesian (X, Y, Z) and rotational (A, B, C) axes together with the closed-loop sensor feedback mechanism for real-time monitoring, adaptive process control, and intelligent multi-axis additive manufacturing.

TABLE 4. Comparative analysis of computational modelling techniques employed for smart-material characterization and process optimization in intelligent 6D printing.

Modelling Technique	Scale	Primary Purpose	Advantages	Limitations
Molecular Dynamics (MD)	Nano	Predict polymer chain behaviour and stimuli response	High material accuracy	Computationally intensive
Finite Element Method (FEM)	Macro	Structural and thermal analysis	Efficient for engineering-scale simulation	Limited molecular representation
MD-FEM coupling	Multiscale	Transfer molecular properties to structural models	Improved predictive capability	Complex implementation
AI-based predictive modelling	Multiscale	Process optimization and defect prediction	Adaptive, real-time capable	Requires large datasets
Digital Twin	System level	Real-time monitoring and lifecycle management	Continuous optimization	High computational and data-integration requirements

C. Optimal Toolpaths for Five-Axis-Printed Smart Structures

The performance of additively manufactured components is significantly influenced by toolpath planning, since deposition trajectory governs filament orientation, interlayer bonding, residual-stress distribution, and overall mechanical behaviour.

Unlike conventional 3D printing, 5D printing uses synchronized translational and rotational movement to deposit material along curved surfaces, allowing deposited filaments to follow principal stress trajectories and thereby improving load transfer, reducing stress concentration, and enhancing structural integrity while minimizing material consumption [15,16,17].

Curved-layer deposition offers advantages over planar printing by reducing the staircase effect, improving surface finish, minimizing support-structure requirements, and increasing tensile and fatigue strength [16,18]. However, five-axis manufacturing substantially increases process-planning complexity, requiring simultaneous optimization of tool orientation, rotational motion, collision avoidance, curvature adaptation, deposition sequence, and material distribution.

Recent advances have introduced AI, machine learning, topology optimization, and multi-objective optimization

algorithms to automate toolpath generation for complex geometries, simultaneously optimizing structural strength, printing time, material utilization, energy consumption, and process stability [28,29,30]. Variations in nozzle orientation, deposition sequence, extrusion temperature, and cooling rate also directly influence polymer chain alignment, crystallization behaviour, interlayer adhesion, and the stimuli-responsive performance of smart materials, so optimal toolpath planning must jointly consider geometric complexity, material behaviour, thermal history, and functional performance.

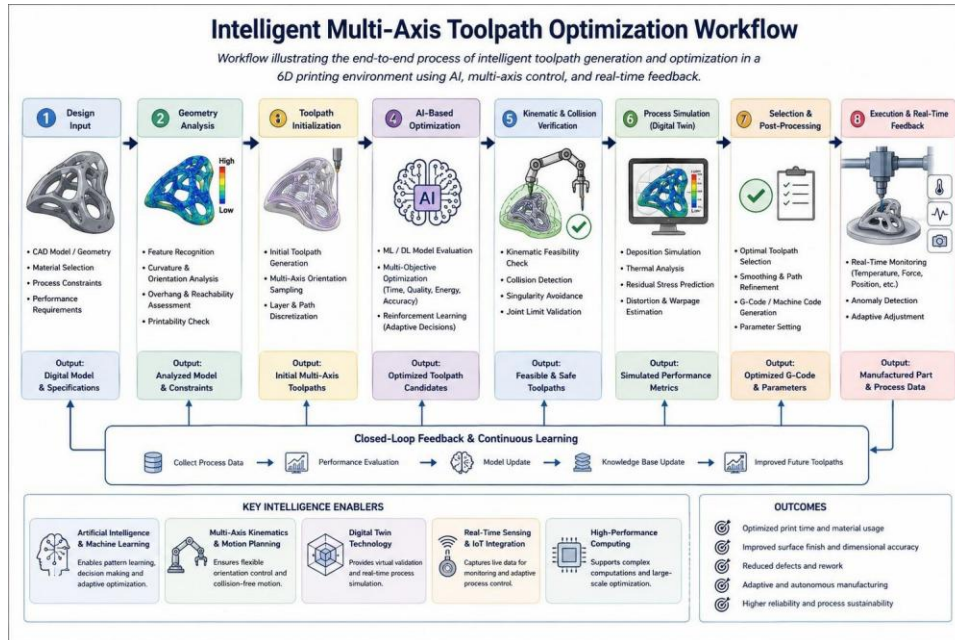


Figure 8. Workflow for intelligent five-axis toolpath optimization illustrating the integration of geometric analysis, multi-axis motion planning, artificial-intelligence-based optimization, smart-material behaviour prediction, and G-code generation for advanced additive manufacturing.

TABLE 5. Key process parameters influencing multi-axis toolpath optimization and their impact on structural performance, manufacturing quality, and functional behaviour in intelligent 5D printing.

Parameter	Influence on Manufacturing	Impact on Printed Component
Nozzle orientation	Controls filament alignment	Improved tensile strength, reduced anisotropy
Layer height	Determines surface quality	Higher dimensional accuracy
Curved toolpath	Follows natural geometry	Reduced staircase effect
Infill pattern	Controls internal load distribution	Improved structural stiffness
Printing speed	Affects deposition stability	Reduced defects, better layer adhesion
Extrusion temperature	Influences polymer flow	Improved interlayer bonding
Cooling rate	Controls crystallization	Enhanced mechanical properties
Smart material activation	Determines functional response	Improved shape-memory behaviour
AI optimization	Adaptive parameter selection	Higher manufacturing efficiency
Multi-axis motion	Enables non-planar deposition	Lower material consumption and support requirements

D. Synthesis: Functional Assessment of 6D-Printed Smart Structures

The functional assessment of 6D-printed structures extends beyond conventional mechanical performance to their ability to autonomously sense, respond, and adapt to changing environmental conditions. Overall functional performance is governed by the interaction between material properties, deposition strategy, process parameters, and external stimuli; molecular chain orientation, interlayer bonding, nozzle trajectory, thermal history, and cooling conditions directly influence accuracy, response speed, shape recovery, structural

stability, and durability. Integrating MD, FEM, AI, and digital twin technologies significantly enhances prediction and optimization of smart-material behaviour before, during, and after fabrication [23,24,25,28]. Digital twin technology in particular establishes a virtual representation of the manufacturing system, allowing continuous monitoring, defect prediction, adaptive process control, and lifecycle performance evaluation through closed-loop feedback. Sensor networks enabling real-time acquisition of temperature, force, displacement, extrusion quality, and dimensional-accuracy data allow immediate detection of process deviations and automatic

parameter adjustment, improving process stability and reducing material waste.

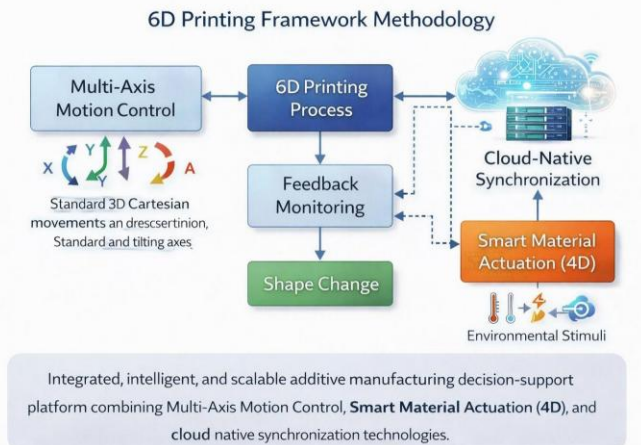


Figure 9. Comprehensive methodology of the proposed 6D Printing Framework (6DPF), illustrating the integration of smart material databases, multi-scale computational modelling, five-axis toolpath optimization, artificial intelligence, digital twin technology, sensor-based closed-loop monitoring, and intelligent additive manufacturing for adaptive smart structures.

V. CHALLENGES IN 5D/6D PRINTING

Although the proposed 6DPF represents a significant advancement in intelligent additive manufacturing, several scientific, technological, and industrial challenges continue to limit its widespread implementation, involving complex interactions among material behaviour, computational modelling, process planning, hardware architecture, and regulatory compliance.

A. Computational and Software Challenges

A primary obstacle to industrial implementation of 5D and 6D printing is the absence of standardized software capable of managing the computational complexity of multi-axis additive manufacturing. Conventional slicing software is developed for planar layer-by-layer fabrication and cannot efficiently generate collision-free deposition paths for complex curved geometries produced via five-axis motion. Curved-layer manufacturing also introduces variation in layer thickness, deposition angle, extrusion rate, and thermal history, which can cause incomplete bonding, internal porosity, and dimensional inaccuracy unless continuously adjusted; recent research has focused on AI-assisted slicing and adaptive toolpath planning to address this [28,29,30]. Seamless integration between CAD models, material databases, MD, FEM, digital twin platforms, and manufacturing control systems is further required, but most existing software environments operate independently, resulting in fragmented workflows and limited interoperability.

B. Material Science and Stimuli-Responsive Challenges

6D printing performance depends on advanced smart materials with reliable, repeatable responses to external stimuli. Despite progress in SMPs, hydrogels, EAPs, LCEs, and magneto-responsive composites, practical implementation remains constrained by lower mechanical strength, reduced

fatigue resistance, and limited long-term durability relative to conventional engineering materials, and repeated stimulus exposure often causes degradation of functional performance and irreversible structural change after multiple activation cycles [19,20]. Material-process compatibility is a further challenge: thermo-mechanical properties required for multi-axis extrusion often differ from those required for stimuli-responsive behaviour, making the development of multifunctional smart materials combining high structural strength with predictable responsiveness a major ongoing research focus.

C. Hardware and Manufacturing Challenges

Intelligent 6D printing requires manufacturing platforms integrating multi-axis robotic mechanisms, precision motion control, real-time sensing, and closed-loop process optimization. Synchronizing multiple translational and rotational axes increases the likelihood of positioning errors, nozzle collisions, layer instability, and cumulative geometric deviation, where even small calibration inaccuracies can propagate throughout fabrication. Acquisition and maintenance costs for five-axis robotic systems, intelligent sensors, high-performance controllers, and advanced computational hardware remain substantially higher than for conventional three-axis systems, limiting accessibility for small- and medium-sized manufacturers.

D. Standardization, Sustainability, and Regulatory Challenges

6D printing currently lacks internationally accepted standards governing material qualification, process validation, quality assurance, and functional performance evaluation, complicating cross-study comparison and limiting industrial confidence in safety-critical applications such as aerospace, biomedical engineering, and defense. Increasing integration of AI, digital twin technology, cloud-based manufacturing, and sensor-enabled smart structures also raises concerns regarding cybersecurity, data privacy, intellectual-property protection, and the ethical use of autonomous manufacturing systems. From a sustainability perspective, recycling strategies, energy consumption, and lifecycle assessment for intelligent products remain insufficiently explored [40,41].

VI. INDUSTRIAL PERSPECTIVES

The evolution from conventional manufacturing to 6D Additive Manufacturing (6D-AM) represents a paradigm shift in intelligent production systems. By integrating multi-axis additive manufacturing, stimuli-responsive smart materials, AI, digital twin technology, and multi-scale computational modelling, the proposed 6DPF extends additive manufacturing beyond geometric fabrication toward adaptive, self-responsive, functionally intelligent components. As industries progress from Industry 4.0 toward Industry 5.0, 6D printing is expected to become a key enabling technology for autonomous manufacturing, mass customization, predictive maintenance, and sustainable production.

Major Challenges Limiting the Industrial Adoption of 6D Printing



Figure 10. Major technological, computational, material, manufacturing, and regulatory challenges limiting the industrial implementation of the proposed 6D Printing Framework.

TABLE 6. Summary of the principal challenges, current limitations, and future research directions for advancing intelligent 5D and 6D printing technologies.

Challenge Category	Current Limitations	Potential Research Directions
Computational & software	Complex multi-axis toolpath generation, fragmented software	AI-assisted slicing; unified CAD–MD–FEM–digital twin platforms
Smart materials	Limited durability, slow response, poor process compatibility	Multifunctional smart materials, nano-engineered composites
Hardware & manufacturing	High equipment cost, calibration errors, sensor integration	Cost-effective robotic systems, adaptive control, real-time monitoring
Standardization & regulation	Lack of testing protocols, certification, cybersecurity concerns	International standards, lifecycle assessment, secure digital manufacturing

A. Aerospace and Defense

Aerospace and defense are among the most promising application areas for intelligent 6D printing due to stringent requirements for lightweight *structures*, mechanical performance, and functional adaptability. Multi-axis deposition enables optimized fibre orientation and reduced support material, improving the buy-to-fly ratio, while smart materials enable adaptive structures capable of autonomously responding to temperature, aerodynamic loading, or environmental conditions—potential applications include morphing wings, self-deploying satellite components, adaptive air inlets,

vibration-control systems, and intelligent thermal-protection structures. Integrating digital twin technology with structural health monitoring further supports predictive maintenance and lifecycle optimization.

B. Architecture, Engineering, and Construction (AEC)

Five-axis concrete printing enables geometrically complex load-bearing structures with minimal support material, while smart construction materials introduce adaptive functionality responsive to environmental conditions throughout a building's service life. Emerging concepts such as adaptive building envelopes, self-regulating façades, and climate-responsive

structural components can dynamically regulate heat transfer, ventilation, and solar radiation, improving energy efficiency and supporting environmentally responsible infrastructure development.

C. Biomedical and Healthcare Applications

Healthcare is one of the fastest-growing application areas, where patient-specific manufacturing and adaptive biomaterials are transforming personalized medicine. Smart biomedical devices fabricated from stimuli-responsive materials can dynamically alter geometry or mechanical properties in response to physiological conditions. Potential applications include self-expanding vascular stents, biodegradable tissue-engineering scaffolds, adaptive orthopedic implants, drug-delivery systems, and shape-changing prosthetics [35,36,37]; multi-axis robotic manufacturing further enables in-situ bioprinting onto curved anatomical surfaces.

D. Soft Robotics, Electronics, and Intelligent Devices

The combination of multi-axis manufacturing and smart materials enables monolithic fabrication of soft robotic systems and intelligent electronic devices in which sensing, actuation, and structural support are integrated into a single component [38,39], including soft robotic manipulators, wearable healthcare devices, flexible electronics, adaptive sensors, and artificial muscles.

E. Manufacturing, Automotive, and Energy Sectors

Intelligent manufacturing systems capable of optimizing material distribution, structural topology, and adaptive functionality can reduce production waste while improving product performance in automotive engineering (adaptive lightweight structures, energy-absorbing safety devices) and renewable energy (self-adaptive turbine blades, responsive solar-tracking mechanisms, intelligent energy-storage components).

F. Industrial Adoption and Future Commercialization

Despite its technological advantages, large-scale industrial implementation of 6D printing remains constrained by practical considerations: current manufacturing environments require substantial advances in AI-driven process planning, standardized software platforms, smart-material development, multi-axis machine reliability, and internationally accepted certification standards before widespread commercialization can be achieved. The transition from laboratory-scale demonstration to industrial production will depend on integrated digital manufacturing ecosystems combining AI, digital twins, real-time sensor feedback, and cloud-based manufacturing platforms, supported by continued collaboration among academia, equipment manufacturers, material developers, and industrial stakeholders.

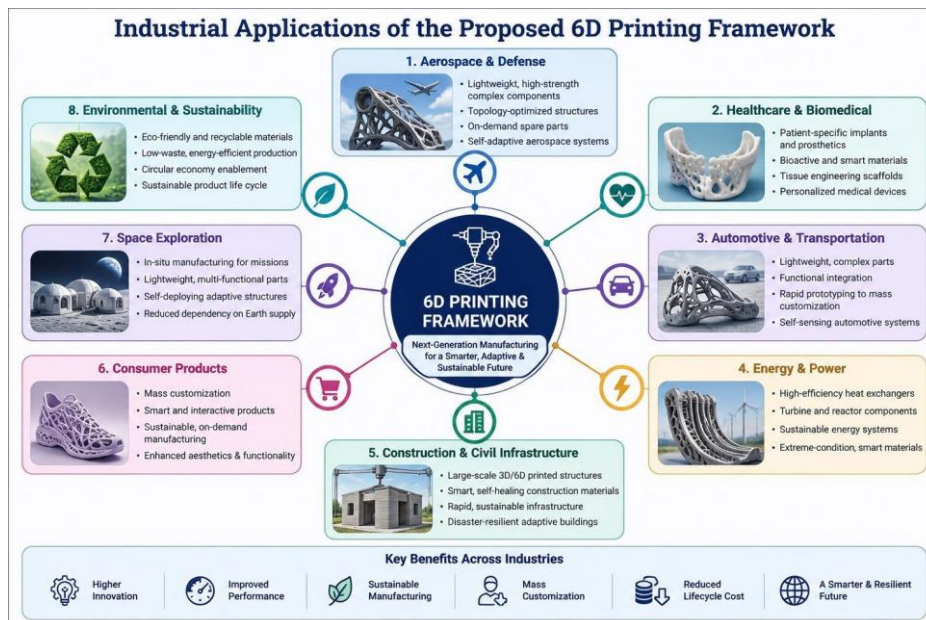


Figure 11. Major industrial sectors benefiting from the proposed 6D Printing Framework, highlighting the integration of intelligent manufacturing technologies for adaptive and high-performance engineering applications.

TABLE 7. Representative industrial applications and potential benefits of the proposed 6D Printing Framework across major engineering sectors.

Industrial Sector	Representative Applications	Primary Benefits
Aerospace & Defense	Morphing wings, deployable satellite structures	Lightweight design, improved structural efficiency
Architecture & Construction	Adaptive façades, intelligent buildings	Energy efficiency, sustainable construction
Biomedical & Healthcare	Smart implants, tissue scaffolds, in-situ bioprinting	Personalized medicine, minimally invasive treatment
Soft Robotics & Electronics	Artificial muscles, wearable devices, flexible sensors	Integrated functionality, reduced assembly
Automotive & Manufacturing	Lightweight components, adaptive cooling systems	Improved fuel efficiency, reduced production cost
Renewable Energy	Smart turbine blades, adaptive solar systems	Enhanced energy efficiency, predictive maintenance

VII. RESULTS AND DISCUSSION

The analysis of the 85 reviewed studies indicates that the evolution from conventional 3D printing toward the proposed 6DPF represents a significant advancement in intelligent additive manufacturing. Unlike traditional layer-by-layer fabrication — limited by planar deposition, anisotropic mechanical properties, and static material behaviour — the integration of multi-axis manufacturing, smart materials, multi-scale computational modelling, AI, and digital twin technology enables adaptive structures capable of responding autonomously to changing environmental conditions.

A. Structural Optimization and Manufacturing Efficiency

A recurring finding across the reviewed multi-axis studies [15,16,17,18] is substantial improvement in structural performance achieved through five-axis curved-layer deposition. Unlike conventional three-axis printing, where material is deposited in planar layers perpendicular to the build direction, multi-axis printing aligns deposition paths with the natural stress trajectories of the component, improving load distribution, reducing stress concentration, minimizing the staircase effect, and enhancing interlayer bonding. Several of the reviewed studies further report reduced support-structure requirements under curved-layer manufacturing, translating to lower material consumption, shorter printing times, and improved surface quality — advantages particularly relevant for lightweight aerospace, biomedical, and automotive applications.

B. Smart Material Integration and Multi-Scale Computational Modelling

The reviewed literature on smart materials [19,20,21,22] and multi-scale modelling [31,33] indicates that the intelligent functionality of 6D printing is fundamentally dependent on integrating stimuli-responsive smart materials with predictive computational modelling. The adaptive behaviour of smart polymers and composites is governed by interactions across multiple physical scales

--molecular chain mobility, nanoparticle dispersion, crystallization behaviour, and thermo-mechanical coupling. Coupling MD (nanoscale material characterization) with FEM (macroscopic structural performance) provides a multi-scale framework capable of predicting shape transformation, mechanical behaviour, thermal response, and structural stability before fabrication, reducing experimental iteration while improving reliability.

C. Artificial Intelligence and Intelligent Process Optimization

A recurring theme across the AI-focused studies reviewed [28,29,30] is the growing role of AI in addressing the computational complexity of intelligent additive manufacturing. The transition from three-axis to 6D printing substantially expands the manufacturing parameter space by adding rotational degrees of freedom together with stimuli-responsive material behaviour, which conventional slicing algorithms are insufficient to optimize. AI-assisted toolpath planning, machine learning, topology optimization, and

predictive modelling are reported to jointly optimize nozzle orientation, extrusion parameters, material distribution, thermal history, and manufacturing efficiency; when integrated with digital twin technology and real-time sensor feedback [23,24,25], these strategies enable adaptive process control and continuous quality monitoring.

D. Industrial Readiness and Current Research Limitations

Although the reviewed studies demonstrate progress in multi-axis manufacturing, smart-material development, and computational modelling, several constraints continue to restrict large-scale industrial implementation: existing software platforms remain fragmented, standardized smart-material databases are still under development, and comprehensive interoperability between CAD systems, computational simulation, AI optimization, and manufacturing equipment has not yet been fully achieved [1,2,4]. The limited availability of multifunctional smart materials with high mechanical performance and predictable stimuli-responsive behaviour, combined with the high cost of multi-axis manufacturing systems and the absence of internationally accepted qualification and lifecycle-assessment standards, further limits commercialization in safety-critical sectors.

E. Synthesis and Future Research Perspective

Overall, the proposed 6DPF provides a comprehensive methodology for integrating advanced manufacturing technologies into a unified intelligent production environment. The combination of smart-material databases, multi-scale computational modelling, five-axis toolpath optimization, AI, digital twin technology, and closed-loop sensor feedback establishes a platform for manufacturing adaptive structures with enhanced structural integrity and autonomous functional behaviour. Realizing the full industrial potential of 6D printing will require continued advances in multifunctional smart materials, AI-driven process planning, standardized computational frameworks, sustainable manufacturing strategies, and real-time digital manufacturing ecosystems [1,4].

VIII. FUTURE WORK

The rapid evolution of multi-axis additive manufacturing, smart materials, AI, and digital twin technologies indicates that 6D printing has the potential to become a key enabling technology of next-generation intelligent manufacturing. Future research should prioritize four directions.

AI/ML across the full workflow. Future platforms should incorporate computer vision, sensor fusion, and deep learning to continuously monitor extrusion quality, temperature distribution, dimensional accuracy, and structural integrity, enabling autonomous adjustment of nozzle orientation, extrusion rate, deposition speed, and thermal conditions [28,29,30].

Next-generation smart materials. Nano-engineered smart composites capable of responding to multiple simultaneous stimuli (temperature, magnetic field, electrical signal, moisture, mechanical loading), together with comprehensive smart-

material databases, are needed to support AI-assisted material selection and improve reliability [19,20,21].

Integrated multi-scale computational frameworks. Real-time synchronization between MD/FEM simulation and

physical manufacturing systems would enable continuous process-parameter optimization, predictive defect detection, and adaptive quality control [24,25,31].

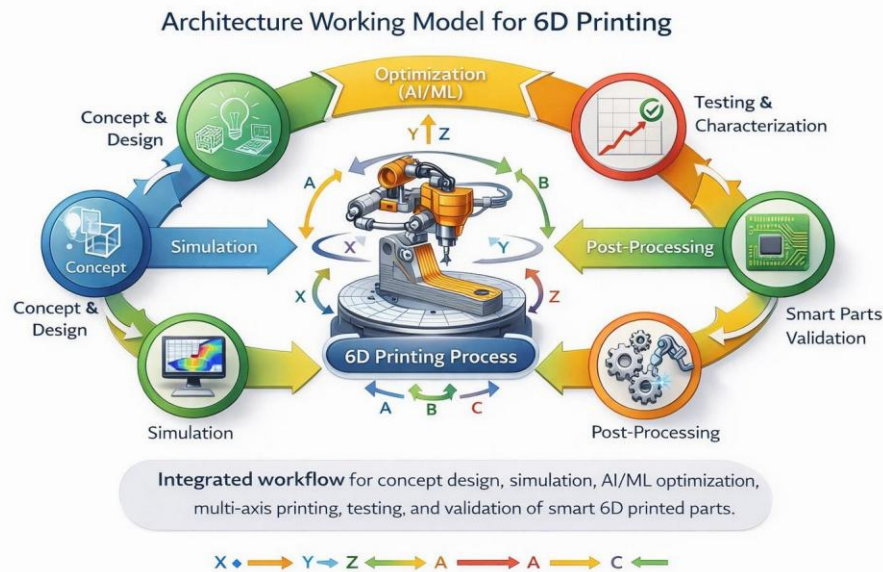
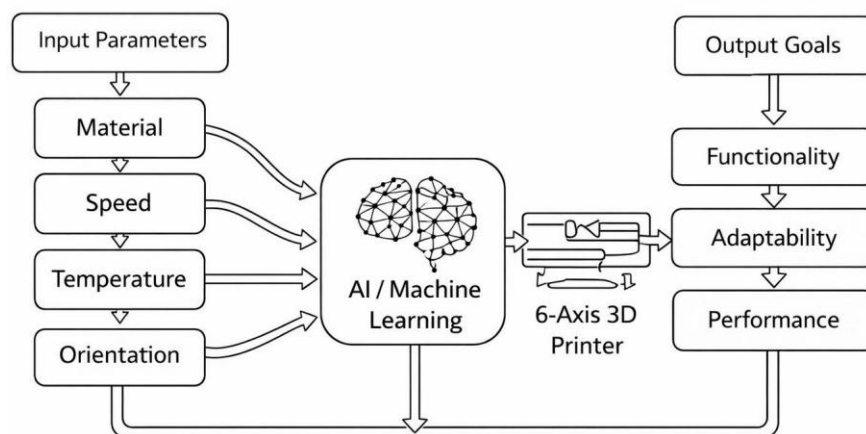


Figure 12. Overall architecture of the proposed 6D Printing Framework (6DPF), illustrating the integration of smart material databases, molecular dynamics (MD), finite element method (FEM), artificial intelligence (AI), digital twin technology, multi-axis toolpath optimization, sensor-based feedback, and intelligent additive manufacturing for adaptive engineering applications.

TABLE 8. Summary of the principal findings obtained from the reviewed literature and their implications for the proposed 6D Printing Framework.

Research Aspect	Major Findings	Implications for 6D Printing
Multi-axis manufacturing	Curved-layer deposition improves strength, reduces support material	Higher structural efficiency, material savings
Smart materials	Stimuli-responsive behaviour enables adaptive functionality	Foundation for intelligent manufacturing
Multi-scale modelling	MD–FEM coupling improves prediction accuracy	Reduced experimental cost, improved reliability
Artificial intelligence	Optimizes toolpaths and process parameters	Autonomous manufacturing, defect reduction
Digital twin	Enables real-time monitoring and predictive control	Improved process stability, lifecycle management
Industrial readiness	Limited by software, materials, cost, and standards	Requires integrated digital manufacturing ecosystems



Algorithmic workflow for optimizing 5D printing parameters using artificial intelligence to achieve targeted smart material responses.

Figure 13. AI-driven workflow for optimizing multi-axis 5D printing parameters through intelligent analysis of process variables, smart-material behaviour, sensor feedback, and predictive modelling to achieve targeted functional responses in the proposed 6D Printing Framework.

TABLE 9. Future research priorities and technological developments required to advance the proposed 6D Printing Framework toward intelligent, autonomous, industrial-scale additive manufacturing.

Research Area	Current Limitation	Future Direction	Expected Impact
Artificial intelligence	Static process optimization	Autonomous AI-driven manufacturing	Intelligent closed-loop control
Smart materials	Limited multifunctionality	Multi-stimuli nano-engineered composites	Improved adaptive performance
Multi-scale modelling	Separate MD and FEM analyses	Fully integrated MD–FEM–digital twin framework	Accurate performance prediction
Multi-axis manufacturing	Complex toolpath planning	AI-assisted adaptive path optimization	Improved structural quality
Software platforms	Fragmented CAD/CAM workflows	Unified intelligent manufacturing platform	Seamless digital manufacturing
Sustainability	Limited recycling strategies	Recyclable smart materials and lifecycle optimization	Environmentally sustainable production
Industrial standardization	Lack of certification protocols	International standards and qualification procedures	Accelerated industrial adoption

Standardized, scalable digital manufacturing infrastructure. Integrated CAD/CAM environments supporting multi-axis toolpath generation, smart-material modelling, AI-assisted optimization, and digital-twin-enabled monitoring, combined with advances in robotic systems, sensor technology, and cloud/edge computing, are required to deploy autonomous 6D printing at industrial scale.

IX. CONCLUSIONS

This review traces the evolution of additive manufacturing from conventional 3D printing to the proposed 6D Printing Framework (6DPF), synthesizing 85 peer-reviewed studies selected through a PRISMA-guided process. The evidence indicates that convergence of multi-axis additive manufacturing, stimuli-responsive smart materials, multi-scale computational modelling, AI, and digital twin technology provides a coherent basis for adaptive, autonomous, high-performance manufacturing systems. Unlike earlier generations of additive manufacturing that focused primarily on geometric complexity, 6D printing introduces intelligent functionality that allows printed structures to respond dynamically to environmental conditions while improving structural integrity and manufacturing efficiency.

The reviewed literature consistently indicates that five-axis manufacturing enhances mechanical performance through curved-layer deposition, optimized filament orientation, and reduced dependence on support structures, while smart materials introduce programmable behaviour through controlled responses to thermal, electrical, magnetic, mechanical, and chemical stimuli. The integration of MD, FEM, and AI-assisted optimization enables prediction of material behaviour and structural performance across multiple physical scales, reducing experimental cost and improving manufacturing reliability.

Nonetheless, several scientific and engineering challenges remain before 6D printing can achieve widespread industrial adoption, including the development of multifunctional smart materials with improved durability, efficient AI-driven multi-axis toolpath optimization, standardized computational frameworks, integrated software platforms, scalable manufacturing systems, and internationally accepted qualification standards. Addressing these challenges will require sustained collaboration among material scientists, mechanical engineers, computer scientists, manufacturing specialists, and industrial stakeholders. On this basis, 6D printing should be regarded not as an incremental extension of additive manufacturing but as a distinct manufacturing paradigm that integrates intelligent materials, advanced computational

modelling, autonomous process optimization, and digital manufacturing technologies within a unified framework.

AUTHOR CONTRIBUTIONS

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DATA AVAILABILITY STATEMENT

No new data were generated in this study. The bibliographic search records supporting the PRISMA analysis (Section 2.1, Figure 2) are available from the corresponding author upon reasonable request.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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