Methods and Applications of BIM-Driven Robots in Complex Structure Machining

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Abstract. BIM-driven robotic construction is becoming an important direction for the precise machining of complex structures due to the growing demand for free-form surfaces, large-scale special-shaped components, and digital fabrication. This paper reviews the key methods and engineering applications of BIM-driven robotic machining, focusing on semantic mapping, data flow integration, toolpath generation, calibration, sensing feedback, and end-to-end workflows from BIM models to robotic execution. In addition, the paper compares the performance of different construction robots, including articulated robotic arms, gantry systems, mobile manipulators, and parallel robots, using four evaluation indicators: positioning accuracy, processing efficiency, engineering feasibility, and cost efficiency. Typical applications in prefabrication, timber machining, and on-site robotic construction are discussed, and the DFAB House project is analyzed as a representative case of building-scale digital fabrication. The review indicates that BIM-driven robotic systems can significantly improve manufacturing flexibility and machining accuracy for complex structures. However, interoperability, semantic loss, on-site positioning, and closed-loop compensation remain major challenges for practical implementation.

Keywords: BIM-driven robotic construction, robotic machining, semantic mapping, digital fabrication, construction robot.

1. Introduction

As sensor technology and robot control technology development, combining Building Information Modeling (BIM) and robot manufacturing for precise processing of complex components is becoming the new hotspot of construction industry. A number of examples of engineering have shown the feasibility and efficiency increasing of the direct digital model-driven machining. Projects such as Digital Fabrication and Building (DFAB) house demonstrate that a closed-loop process, spanning from digital design to on-site or factory-based fabrication, can significantly enhance production efficiency and flexibility for complex components [1].

At the research level, the number of publications in this field has grown rapidly. The research trends are changing from digital model-driven to full process control which includes design sensors and real-time control. Meanwhile, there is widespread interest within the academic community in how to reliably transform geometric and semantic information in BIM into executable robotic paths and machining instructions [2]. Current research into BIM-driven automated workflows, previous work has proposed automatically mapping BIM data to inputs for robotic simulation and executable tasks, thereby enabling accessibility analysis and process feasibility assessment, significantly improving simulation modelling efficiency and supporting manufacturability verification during the design phase [3]. However, there are still significant interoperability and semantic mapping issues between BIM and robot manufacturing. Computational design is often used as a key tool to establish a bridge between BIM and robotic systems. The lack of unified middleware and semantic standards is the main obstacle hindering the implementation of end-to-end engineering applications [4].

Based on the background above, this thesis reviews the specific scenario of complex structure machining with the structure “method-application and performance evaluation-typical case-conclusion and prospect”. Further comparing the ability of different construction robots in complex structures with positioning accuracy, processing speed, engineering feasibility and cost efficiency,

this paper aims to provide reference for robot selection, construction organization and process decision-making.

2. The methods that BIM-driven robots in complex structures machine

2.1. Integrate architecture and data flow

The primary goal of integrating architecture is to transmit the design intent and process semantics in BIM to robot execution layer reliably to make the link from processing traceable and enforceable. Therefore, the semantic fields that are required for machining such as component tolerances, assembly datums, fixture anchors, material parameters, and accessibility constraints, must be included when exporting BIM, which directly determines subsequent feature recognition and process decisions. In a review of the interoperability between BIM and robot manufacturing, Anane et al. pointed out that the main bottlenecks of end-to-end engineering are semantic loss and format mismatch. By using semantic templates and computational design scripts as intermediate layers, the information loss can be significantly reduced, and the automation of simulation and path generation can be improved [4].

2.2. End-to-end workflow

End-to-end workflows from semantic mapping to field execution often included the annotation and export of BIM, geometric cleanup and feature extraction, toolpath generation, robot-specific post-processing, simulation verification, and on-site execution and closed-loop feedback. Complex free-from surfaces and large-scale special-shaped parts have a high requirement for precision. The stiffness of the robot body, dynamic response and tool-workpiece interaction will introduce errors in the path execution, so the kinematic constraints and singular shape avoidance must be considered at the same time when the path is generated, and the Cartesian trajectory is mapped to the robot joint trajectory in the post-processing step to ensure executability. Mainstream engineering for precision improvement includes pre-construction high-precision calibration, online sensing measurement and sensor fusion, and measurement-based closed-loop compensation. Ji and Wang conclude in a review of industrial robot milling that calibration and closed-loop compensation have been experimentally verified in significantly reducing positioning errors and improving surface topography [5]. For specific materials and component types, such as cross-laminated timber (CLT) large plates, studies have proposed to embed manufacturability checks into BIM path generation to identify process limitations and automatically generate adapted machining paths during the design phase, thereby reducing on-site implementation risks [6]. In practice, laser tracking and high-precision measurement equipment are often used to establish datum coordinate systems and support high-precision in-situ registration and calibration, and these methods have been proven to reduce coarse positioning errors to the submillimeter level and improve machining consistency in industrial applications [7].

3. Application areas and performance evaluation

Robots show two obvious advantages in the processing of complex structures: one is the flexibility to handle large-scale and irregular geometries, and the other is to realize the direct closed loop from digital design to manufacturing. Firstly, in the field of prefabrication and assembly of building components, BIM-based robot simulation and automated prefabrication can significantly improve connectivity and simulation modeling efficiency from design to simulation, thereby reducing the risk of on-site conflicts and rework [3]. Practices such as DFAB House demonstrate the potential of robots for the digital production of large-scale concrete and timber components.

Secondly, in large-scale wood processing, especially in CLT processing, the researchers proposed a target path planning method that automatically generates manufacturable paths from BIM to complete the manufacturability check and output the processing tasks that the robot can perform in the design stage, which plays an important role in improving the machining feasibility and estimating labor costs in advance [6]. In order to facilitate engineering selection, this study uses four indicators

as the evaluation framework: positioning accuracy, processing speed or single piece cycle, engineering feasibility (including accessibility and assembly match), and cost efficiency [3,5]. Based on this framework, the advantages and disadvantages of different types of construction robots in engineering applications can be summarized as follows.

Articulated industrial robotic arms (six degrees of freedom) have the advantages of large working space and modularity of end tools, suitable for handling complex freeform surfaces and multi-process switching. However, the inherent structural stiffness limitations make static and dynamic deformation the main factors affecting the machining accuracy, so stiffness modeling, attitude optimization, and calibration compensation are usually required to improve absolute accuracy [5,7]. Articulated arms remain the preferred choice in the pursuit of flexibility and versatility, but achieving sub-millimeter accuracy often requires additional stiffening devices or in-line compensation.

Gantry systems are known for their linear transmission and high mechanical rigidity, which can achieve more stable positioning accuracy and shorter single-piece cycles in large-scale, linear, or coverage machining tasks, making them ideal for large-scale component processing in factory prefabrication [8]. The disadvantage is that field deployment is limited by site and installation and is not as flexible as articulated arms.

The mobile chassis + robotic arm (mobile manipulator) has significant accessibility and flexibility advantages in the field and is suitable for on-site trimming or assembly repair. Its positioning accuracy relies on external positioning systems (e.g., Light Detection and Ranging (LiDAR)/vision/external datum) and real-time registration algorithms, which can be improved to an acceptable range by fusing positioning and sensing, but this usually increases system complexity and time costs [7]. Therefore, mobile manipulators are more suitable for scenarios that require in-situ processing and high accessibility but require low absolute accuracy.

parallel robots or parallel-series hybrid mechanisms have high rigidity and excellent dynamic performance in a small work envelope, making them suitable for high-speed and high-precision detail processing or batch detail processing, but their working range is limited, and they are usually used as specialized subsystems in conjunction with other robots [9].

In summary, the application scenario determines the preferred system: the preferred system is the gantry for large-scale factory, the articulated arm is preferred for complex free-form surfaces and multi-processes, the mobile manipulator is preferred for on-site trimming, and the parallel mechanism is preferred for high-speed detail processing [5,8,9].

Challenges and research gaps include export errors due to interoperability and semantic loss, inadequate on-site fixtures and positioning strategies, limited flexibility and accessibility of robots in the field environment, and imperfect economic feasibility assessment system based on engineering costs. Future research should focus on incorporating machining-related tolerances and assembly semantics into BIM, developing standardized intermediate semantic mapping layers, and constructing calibration and closed-loop compensation processes that can be dynamically adjusted in the field to improve the feasibility of complex structural machining.

4. DFAB house overall case

DFAB House is a building-scale digital construction demonstration project focused on verifying whether BIM-driven robotic construction can move from laboratory research to real-world building-scale applications. The project integrates multiple robotic processes into a single building platform to discuss complex structures in terms of design freedom, manufacturability, and engineering organization. The results show that the combination of digital design and robot construction can significantly improve the manufacturability of complex components and provide a new technical path for building industrialization [1].

The application of Mesh Mould is focused on on-site robot construction. This technology uses mobile robots and custom end-effectors to complete the in-situ fabrication of complex reinforced concrete walls in a non-factory environment. It breaks through the limitations of traditional formwork

construction and component shape, enabling robots to directly participate in the on-site shaping of complex geometric components. Relevant studies have shown that this method not only improves the geometric freedom of components but also enhances the accessibility and adaptability of robots on construction sites, reflecting the advantages of robots in on-site processing of complex structures [1].

Structural stay-in-place formwork mainly reflects the engineering capabilities of robots in the prefabrication of non-standard concrete structures. This technology completes the manufacturing of complex structural components through robotic fixed formwork or in-situ forming. The conclusion is that robots can not only manufacture traditional regular components but also serve the production of non-standard and large-scale building components, thereby playing a role in reducing template dependence, improving manufacturing consistency, and enhancing the freedom of structural expression [1].

At the heart of Smart Dynamic Casting lies the prefabrication of custom load-bearing columns using robotic sliding dies and variable molds. Compared with traditional fixed formwork, this technology can dynamically adjust the forming process according to component needs, thus balancing standardized production with non-standard component manufacturing. The results show that the robotized dynamic pouring process can not only improve the manufacturing efficiency of complex structural components, but also reduce material waste and template consumption, showing strong advantages in engineering feasibility and cost control [10].

In summary, DFAB House's related cases show that BIM-driven robot construction can improve the manufacturing accuracy and geometric freedom of complex structures, and also show clear advantages in on-site construction, prefabrication, and material optimization. They also show that the key to robotic building applications is not only "whether it can be processed", but also how to integrate design information, construction technology and site conditions to achieve truly landable complex structure processing [1,10].

5. Conclusion

BIM combined with robotics can directly translate design semantics into executable manufacturing instructions, improving design freedom and manufacturing accuracy when working with freeform surfaces and large-scale special-shaped parts. To achieve engineering implementation, it is necessary to focus on interoperability and semantic standardization, rapid calibration and registration processes, and sensor-based online closed-loop compensation. The promotion of standardized middle layers and open evaluation benchmarks will help accelerate industrial application in this direction.

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