

博 士 学 位 论 文

大型复杂构件原位制造中 跨尺度测量与机器人控制关键技术研究

Research on Key Technologies of Cross-Scale Measurement
and Robotic Control in In-Situ Manufacturing
for Large Complex Components

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摘 要

以大飞机机身、空间站舱体为代表的大型航空航天结构件是国家整体制造实力的重要体现。以大型航天舱体为例，其外表面有上百个满足亚毫米级加工精度的载荷支架，且部分支架间存在强关联关系，需互为加工基准。鉴于大型航天构件对尺寸精度与结构完整性的严格要求，采用整体加工模式已成为必然选择。然而，传统基于龙门多轴数控机床的“包容式”加工模式存在制造成本高、加工行程受限等局限。目前，以工业机器人为加工装备执行体的制造系统，具有成本低、可重构性强、运动灵活性高等优点，但在大型复杂构件制造中仍面临跨尺度测量精度、加工对刀精度与机器人执行精度等多重技术挑战。

为解决大型航天构件难以高精高效的制造难题，本文将激光扫描仪集成至机器人加工末端，并结合激光跟踪仪与双目视觉构建多模式融合跨尺度原位测量系统，实现了覆盖大型构件全加工场景的高精测量。同时，通过开发测量-加工闭环控制的机器人高精定位加工方法，将测量过程融入加工流程，形成测量加工一体化的制造模式，实现了机器人的精准对刀。然后，研发了基于动力学模型的前馈控制与关节位置实时反馈控制的数控机器人系统，显著提升了机器人加工轨迹精度。最后，搭建一套集成高精度测量设备和先进控制算法的机器人原位制造系统，并通过对大型航天复杂构件进行测量和加工实验，验证了该系统的精度和有效性。具体研究内容如下：

(1) 针对大型复杂构件表面特征种类繁多、分布跨度大、加工基准不统一、制造精度要求高的难题，本文构建了覆盖全加工场景的“激光跟踪仪全局定位+双目视觉整体测量+线激光局部扫描”跨尺度原位测量系统。同时，提出了一种基于图像先验和点云配准算法的融合测量方法：首先，利用图像提供的先验信息快速删除大量冗余点云，再通过基于几何特征匹配和双向 KD-tree 的 FM-BiKD-ICP 算法完成多视角支架点云的高精配准和特征提取；然后，基于特征尺度不变性实现了多源测量数据融合。实验结果表明：在大型航天复杂构件制造中，跨尺度原位测量系统的局部测量均方根误差小于 0.015mm，点云处理效率提升约为 75%；全局测量时，平均精度比视觉测量系统提升约 49.4%，整体效率相比手持扫描仪提升超过 90%。通过设备-算法-数据的三层融合，有效实现了多源测量数据的全局融合统一、大型航天构件的整体重建及局部特征的高精测量。

(2) 为解决传统制造方式测量过程游离于加工流程之外、难以满足大型复杂构件高质高效制造需求的问题，本文提出了基于测量加工闭环控制的机器人高精定位加工方法，通过将测量功能融入到加工流程中，使机器人能够自主感知即将进行作业的加工场景和大型复杂构件的特征。首先，阐述了机器人末端执行器“加工-检测-调整”的闭环

控制工作原理及其坐标系转化之间的关系。然后，融合多位姿测量误差优化、基于激光跟踪仪的光学 TCF 和多轴线拟合最近点形成了多参量最佳拟合标定方法，可以准确关联加工系统和工件间的位姿关系，实现了加工机器人的精准对刀。最后，搭建测量加工一体化末端执行器，并对其关键参数进行标定。机器人的对刀和加工精度实验结果表明：在 10 m 作业范围内，机器人对刀的平均误差为 0.083mm，最大误差为 0.096mm，且测量加工闭环控制策略显著提升了机器人的加工精度。

(3) 针对工业机器人难以满足大型复杂构件亚毫米级加工精度的问题，提出了一种基于数控驱动机器人的闭环控制系统性能提升方法。首先，设计了数控系统直驱机器人的全新控制架构，并结合关节位置光栅，构建了基于关节转角实时反馈的闭环控制系统。然后，采用多级辨识法逐步确定运动学参数，通过虑及 Pieper 准则的运动学补偿和关节轴间耦合插补算法，显著提升了末端定位精度。最后，通过基于动力学模型的前馈控制与反馈控制相结合的控制策略，加快驱动器内部的误差收敛速度，实现机器人高动态响应控制，改善机器人的动态性能，从而提高了复杂动态环境中的轨迹精度。机器人圆度轨迹测试实验结果表明：补偿后的控制系统大幅改善了机器人动态轨迹形状，使其大部分与理想圆接近，仅留下轻微的过冲行为，双向圆度偏差为 166.3 μm ，比库卡控制系统的误差降低约 60%。

(4) 基于前文的研究，完成了“跨尺度多模式融合原位测量系统-测量加工一体化末端-数控驱动闭环加工机器人”机器人原位制造系统的总体架构设计及搭建，并对其精度和功能进行实验验证。首先，对原位制造系统进行测量精度验证实验，在 2 m 测量范围内，系统测量平均误差为 0.024 mm，标准差和均方根误差均小于 0.038 mm。然后，按照国际标准对机器人性能进行评估，与库卡控制系统相比，机器人的绝对定位精度最大误差从 3.58 mm 降低至 0.39 mm，最大位置轨迹误差从 1.96 mm 降低至 0.22 mm。最后，对大型复杂构件开展加工精度验证实验，航天支架安装孔的制孔和铣削加工精度均符合制造要求，且测量系统原位检测精度也满足加工需求。其中，大跨距关联支架间的位置误差为 0.062 mm，角度偏差为 0.079°。实验结果表明：该机器人原位制造系统各项指标均满足大型复杂构件的精密制造需求。

关键词：大型复杂构件；跨尺度融合测量；测量加工一体化；数控驱动机器人；机器人原位制造系统

ABSTRACT

Large aerospace structural components, such as aircraft fuselages and space station modules, represent a critical measure of a nation's overall manufacturing capabilities. Taking large aerospace modules as an example, their external surfaces feature hundreds of load-bearing brackets that require sub-millimeter-level machining precision. Some of these brackets have strong interdependencies, needing to serve as mutual references during machining processes. Given the stringent requirements for dimensional accuracy and structural integrity in large aerospace components, an integrated machining approach has become an inevitable choice. However, the traditional "enclosure-type" machining mode, which relies on gantry-style multi-axis CNC machines, is limited by high manufacturing costs and restricted machining range. In contrast, manufacturing systems that use industrial robots as processing executors offer advantages like lower costs, strong reconfigurability, and high mobility. Despite these benefits, using industrial robots for large, complex components still presents significant technical challenges, particularly in achieving cross-scale measurement accuracy, precision in tool alignment, and execution accuracy of the robots themselves.

To address the challenges of achieving high precision and efficiency in manufacturing large aerospace components, this paper integrates a laser scanner into the robotic end-effector. Alongside a laser tracker and binocular vision, this setup establishes a multi-mode fusion cross-scale in-situ measurement system, enabling high-precision measurement across all processing scenarios of large components. Simultaneously, by developing a robot high-precision positioning and processing method with a measurement-processing closed-loop control, the measurement process is integrated into the manufacturing workflow, forming a unified measurement and processing model that achieves precise tool alignment for the robot. Subsequently, a CNC robot system based on a dynamic model was developed, utilizing feedforward control combined with real-time feedback control of joint positions. This significantly improves the accuracy of the robot's processing trajectory. Finally, an in-situ manufacturing system was constructed, integrating high-precision measurement equipment and advanced control algorithms. The system's accuracy and effectiveness were validated through measurement and processing experiments on complex large aerospace components. The specific research content is as follows:

(1) In response to the challenges associated with the diverse surface features, extensive distribution, inconsistent machining reference points, and high precision requirements of large complex components, this study constructs a cross-scale in-situ measurement system that encompasses the entire machining scenario, utilizing "laser tracker global positioning, stereo vision overall measurement, and line laser local scanning." Additionally, we propose a hybrid

measurement method based on image priors and point cloud registration algorithms. This method first uses the prior information from images to quickly eliminate a significant amount of redundant point cloud data. Then, the FM-BiKD-ICP algorithm, which employs geometric feature matching and a bidirectional KD-tree, achieves high-precision registration and feature extraction of multi-view point clouds. Subsequently, multi-source measurement data fusion is accomplished based on feature scale invariance. Experimental results indicate that, in the manufacturing of large aerospace complex components, the root mean square error of local measurements from the cross-scale in-situ measurement system is less than 0.015 mm, with a point cloud processing efficiency increase of approximately 75%. During global measurements, the average accuracy improves by about 49.4% compared to visual measurement systems, while overall efficiency is enhanced by over 90% in comparison to handheld scanners. Through the three-tier integration of equipment, algorithms, and data, we effectively achieve the global unification of multi-source measurement data, overall reconstruction of large aerospace components, and high-precision measurement of local features.

(2) To address the issue of traditional manufacturing measurement processes being detached from the machining workflow and unable to meet the demands for high quality and efficiency in the fabrication of large complex components, this paper proposes a robotic high-precision positioning machining method based on measurement-processing closed-loop control. By integrating measurement functions into the machining workflow, the robot can autonomously perceive the upcoming machining scenario and the features of large complex components. First, we elucidate the working principle of the robotic end effector's "machining-detection-adjustment" closed-loop control and its relationship regarding coordinate transformation. Next, we develop a multi-parameter optimal fitting calibration method that integrates multi-pose measurement error optimization, optical Tool Center Point (TCP) based on laser tracking, and multi-axis line fitting for nearest points. This method accurately correlates the pose relationship between the machining system and the workpiece, enabling precise tool alignment for the machining robot. Finally, an integrated measurement and machining end effector is constructed, and its key parameters are calibrated. The results of the robot's tool alignment and machining precision experiments indicate that within a working range of 10 meters, the average tool alignment error is 0.083 mm, with a maximum error of 0.096 mm. Furthermore, the measurement-processing closed-loop control strategy significantly enhances the machining accuracy of the robot.

(3) To address the challenge of achieving sub-millimeter machining accuracy for large, complex components with industrial robots, we propose a method for enhancing the performance of closed-loop control systems based on CNC-driven robots. First, we design an innovative control architecture for direct-drive CNC systems and, in conjunction with joint

position encoders, a closed-loop control system based on real-time joint angle feedback was established. Next, we employ a multi-level identification method to systematically determine kinematic parameters. By incorporating kinematic compensation based on the Pieper criterion and a joint coupling interpolation algorithm, we significantly improve the end-effector positioning accuracy. Finally, we combine a control strategy that integrates feedforward control based on the dynamic model with feedback control to accelerate the error convergence speed within the actuators, thereby achieving high dynamic response control for the robot and enhancing its dynamic performance. This improvement results in increased trajectory accuracy in complex dynamic environments. The results of the robotic circularity trajectory test indicate that the compensated control system substantially enhances the dynamic trajectory shape of the robot, with most trajectories closely aligning with the ideal circle, leaving only slight overshoot behavior. The bi-directional circularity deviation is measured at 166.3 μm , representing a reduction of approximately 60% compared to the error of the KUKA control system.

(4) Based on the preceding research, we complete the overall design and construction of the “Cross-Scale Multi-Mode Integrated In-Situ Measurement System - Measurement and Processing Integrated End-Effectors - CNC-Driven Closed-Loop Processing Robot” in-situ manufacturing system and conduct experimental validation of its accuracy and functionality. First, we perform measurement accuracy validation experiments on the in-situ manufacturing system. Within a measurement range of 2 meters, the system exhibits an average measurement error of 0.024 mm, with both the standard deviation and root mean square error being less than 0.038 mm. Next, the robot's performance is evaluated according to international standards. Compared to the KUKA control system, the maximum absolute positioning error of the robot decreases from 3.58 mm to 0.39 mm, and the maximum positional trajectory error reduces from 1.96 mm to 0.22 mm. Finally, we carry out accuracy validation experiments for machining large, complex components. The drilling and milling accuracy of the installation holes on aerospace brackets meets the manufacturing requirements, and the in-situ detection accuracy of the measurement system also satisfies the processing demands. Notably, the position error between widely spaced associated brackets is 0.062 mm, with an angular deviation of 0.079°. The experimental results indicate that all performance metrics of this robot in-situ manufacturing system meet the precision manufacturing requirements for large, complex components.

Key Words : Large-scale complex components; Cross-scale fusion measurement; Integrated measurement and machining; CNC-driven robot; Robot in-situ manufacturing system