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# Design of a Collaborative Scanning System for Mobile Robots Aimed at Large-Size Components

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## ABSTRACT

High-precision and full-coverage 3D scanning of large and complex components such as aerospace structures, wind turbine blades and high-speed train car bodies is an important technical demand in the development of high-end manufacturing. Traditional fixed measuring equipment is limited by its operating range, while handheld scanners suffer from low efficiency and heavy reliance on manual operation. To address these issues, this paper designs a collaborative scanning system for mobile robots oriented to large-size components. An intelligent scanning system with autonomous navigation and path optimization capabilities is developed by equipping a mobile robot platform with a six-axis robotic arm and a 3D scanner. The research focuses on hardware system integration and point cloud data processing, with emphasis on optimizing the point cloud denoising parameters based on the SOR algorithm and the point cloud registration method based on RMFD+ICP fusion. This system scheme effectively improves the automation level and data quality of 3D measurement for large-size components, and provides a theoretical basis and technical support for practical engineering applications.

## KEYWORDS

Large-size Components; Mobile Robots; 3D Scanning; Point Cloud Processing

## 1. INTRODUCTION

With the rapid development of high-end manufacturing, fields such as aerospace, energy equipment and rail transit have put forward increasingly high requirements for the processing accuracy and surface quality of large and complex components including aircraft fuselages, wind turbine blades and high-speed train car bodies. Such components are generally characterized by large overall dimensions, complex free-form surfaces and poor deformation resistance. Traditional fixed coordinate measuring machines (CMMs) are restricted by their measurement range, and handheld scanners are inefficient and highly dependent on manual operation. Neither of them can achieve high-efficiency and full-coverage automatic detection of large-size components. Integrating industrial robots with mobile platforms to form a mobile robot machining system can greatly expand the working space and operational dexterity, providing a new technical approach for the automatic 3D scanning of large-size components [1]. The mobile robot collaborative scanning system designed in this paper breaks through the technical bottleneck of large-range and high-precision 3D measurement through the cooperative control of mobile chassis and robotic arm, multi-sensor fusion acquisition, intelligent path planning and efficient point cloud processing, and can provide strong technical support for the online detection link of intelligent manufacturing.

Current domestic and foreign research mainly focuses on three directions: composite mobile robots, detection systems for large-size components, and point cloud data processing. In the field of composite mobile robots, mobile manipulators combine spatial motion capability with flexible operation characteristics, and integrate multi-domain technologies such as automatic control, sensing and artificial intelligence, having become an important part of the advanced manufacturing field. Scholars have carried out research on the modeling and calibration of 3D scanning robot systems based on mobile manipulators [2]. Internationally, mobile manipulators such as the Fetch series by Fetch Robotics, HREB jointly developed by Carnegie Mellon University and Intel, and KUKA Moiros from Germany have been applied to warehousing services, household operations, aircraft skin drilling and assembly, and other scenarios. Domestically, the intelligent application development platform of wheeled mobile robots and the six-axis ultra-light humanoid robotic arm have also achieved high-precision autonomous navigation and complex operations. However, most of the current domestic and foreign mobile machining systems are oriented to operational tasks such as drilling and welding, and systematic research on automatic 3D scanning specifically for large components is still relatively weak. In terms of detection systems for large-size components, 3D scanners generate point cloud data by capturing the geometric shape and surface features of objects, and the key to automatic laser scanning is the rational planning of sampling points and scanning paths. Domestic research on product 3D scanning detection based on industrial robot systems has been carried out [3]. Among them, Liang Yande et al. proposed a solution of "industrial robot + 3D scanner", planned the optimal scanning path based on the chord length discretization method and the minimum enclosing sphere theory, filled the missing scanning areas, and improved the scanning accuracy and efficiency by utilizing the motion stability of robots, providing a practical reference for the automatic scanning of large-size components [4]. In the aspect of point cloud data processing, as a key link of the mobile robot collaborative scanning system, domestic research started late but developed rapidly. Filtering methods based on wavelet analysis have been proposed [5], and point cloud fusion of UAV aerial survey and terrestrial laser scanning has also been realized [6]. However, there are obvious shortcomings in the autonomy of hardware equipment, point cloud matching accuracy and the efficiency of filtering algorithms. Internationally, a complete system of LiDAR 3D imaging simulation has been formed, open-source tools such as PCL have promoted the low cost of 3D reconstruction, and real-time processing of point clouds in multi-robot collaboration has become a research hotspot. On the whole, the current research still has problems such as imperfect specialized integration schemes for 3D scanning of mobile manipulators, lack of systematic design for multi-sensor fusion and hand-eye calibration, and difficulty in balancing the registration efficiency and accuracy of massive low-feature point clouds, which are also the key research directions of this paper.

Focusing on the overall architecture of the mobile robot collaborative scanning system, this paper carries out research work in two aspects: first, hardware system integration and cooperative control, integrating mobile platforms and robotic arms to build an integrated scanning execution unit, building a 3D scanning subsystem with reference to the modeling ideas of existing 3D scanning systems for mobile manipulators, and realizing large-range and high-precision scanning data acquisition through multi-sensor fusion design; second, optimization of point cloud data processing methods, focusing on overcoming the optimization problems of key algorithms such as point cloud denoising and registration, and improving the quality of point cloud processing.

## 2. OVERALL SYSTEM DESIGN

### 2.1. System Construction

The core of hardware system construction is the selection and integration of the composite robot platform and the 3D scanning subsystem. The composite robot platform adopts the Bono mobile robot as the mobile chassis (to achieve large-range scanning coverage), matched with the WFT six-axis robot as the scanner clamping and motion execution unit. The two are physically connected with reserved ROS communication interfaces, and integrated with LiDAR and obstacle avoidance sensor modules to ensure operational safety. The 3D scanning subsystem fixes the Hexagon laser scanner at the end-effector of the robotic arm through a special bracket. At the hardware coordination level, the host computer serves as the core, connecting the robot and the scanner through hardware interfaces to realize instruction issuing and data return. The optical tracking system captures the pose information of the scanner and transmits it to the host computer, completing the hardware coordination for the unification and mosaicking of the multi-view point cloud coordinate system, and providing support for subsequent data processing.

The system software architecture is built based on the Ubuntu 20.04 operating system and the ROS Noetic framework to realize the integrated and cooperative operation of functions such as robot control, sensor driving and point cloud processing. The architecture is divided into three layers: the driver layer, the algorithm layer and the application layer. The driver layer is responsible for the communication adaptation of hardware and software, converting upper-layer instructions into executable signals for hardware to ensure the stable operation of equipment; the algorithm layer integrates core algorithms such as path planning and point cloud processing, undertaking intelligent operational tasks such as path calculation and data optimization; the application layer realizes functions such as scanning task management, point cloud visualization and error analysis, connecting with actual detection requirements and providing operation and result output interfaces.

## 2.2. System Technical Route

The technical route of the system is developed around the demand for high-precision 3D scanning of large-size components, as follows: first, complete the hardware system construction, including equipment selection, mechanical integration and sensor adaptation of the composite robot platform and 3D scanning subsystem, and build a stable hardware operation carrier; then deploy the system software architecture, complete the software development and debugging of the driver layer, algorithm layer and application layer based on the Ubuntu 20.04 operating system and ROS Noetic framework to realize the cooperative communication of hardware and software; on this basis, complete environmental modeling through the mobile robot equipped with LiDAR to provide basic data for path planning; generate a full-coverage optimal scanning path through software algorithms based on the environmental model and component parameters; the mobile robot and robotic arm drive the scanner cooperatively to complete the point cloud data acquisition of large-size components, and simultaneously realize the unification of the multi-view point cloud coordinate system through the optical tracking system; the collected point cloud data is optimized by algorithms such as SOR denoising and RMFD+ICP registration, and then the surface reconstruction is carried out to generate the 3D model of the component; finally, the reconstructed model is compared with the original design model to complete the dimensional error analysis and detection report output, forming a complete scanning and detection technical process for large-size components.

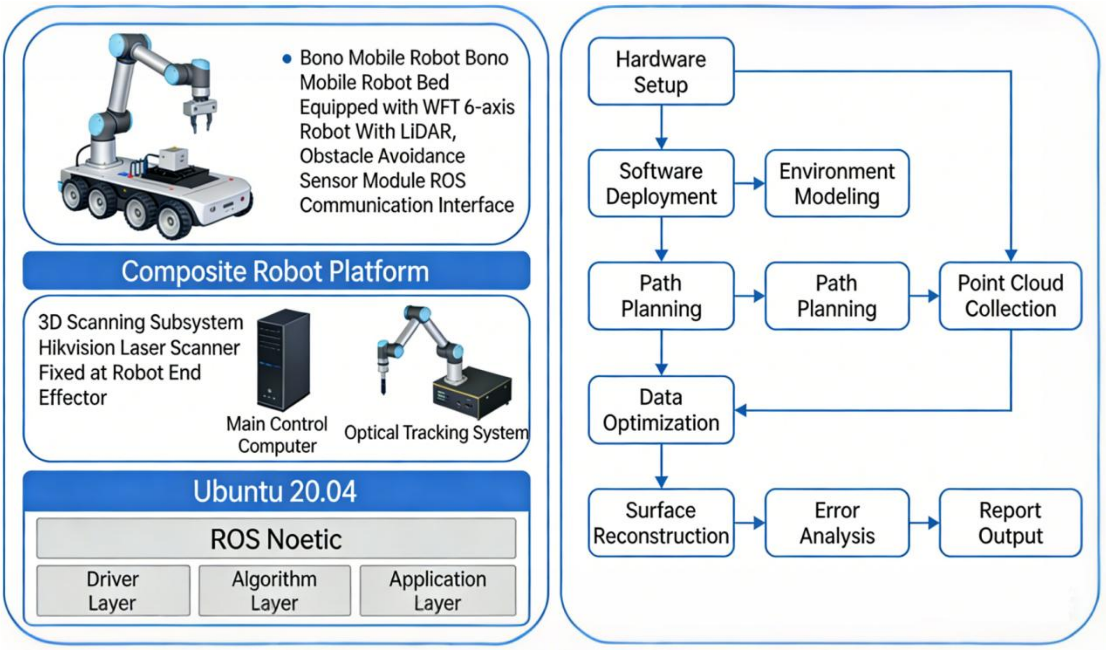

**Figure 1.** Overall System Design

# 3. RESEARCH ON POINT CLOUD DATA PROCESSING METHODS

As a key link of the mobile robot collaborative scanning system, the effect of point cloud data processing directly determines the accuracy and integrity of the 3D model. Aiming at the massive, noisy and low-feature point cloud data generated in the scanning process of large-size components, this paper focuses on optimizing two key algorithms of point cloud denoising and registration, solving the problems of low efficiency, poor accuracy and insufficient adaptability of traditional methods, and realizing the efficient processing and optimization of point cloud data.

## 3.1. Point Cloud Denoising: Parameter Optimization of the SOR Algorithm

Point cloud data collected by 3D laser scanning generally has problems such as uneven density and outlier noise, which are mainly caused by factors such as construction site dust and environmental interference. Existing methods such as bilateral filtering, radius filtering and Gaussian filtering have shortcomings such as limited applicable scenarios and strong subjectivity in parameter setting. This paper adopts the Statistical Outlier Removal (SOR) algorithm to accurately remove outlier noise points, and improves the denoising adaptability and point cloud fidelity by optimizing the core parameters of the algorithm.

The core principle of the SOR algorithm is based on statistical analysis, distinguishing the main points from outlier noise points by judging the spatial distribution difference between each point in the point cloud data and its neighboring points. Its core derivation process is as follows: first, index the original point cloud data set $P = p_1, p_2, \dots, p_n$ by using the KD-tree data structure to quickly search for k neighboring points $N_i = p_{i1}, p_{i2}, \dots, p_{ik}$ of each point $p_i$; calculate the average distance $d_i$ from the point $p_i$ to its k neighboring points, with the calculation formula as follows:

$$d_i = \frac{1}{k} \sum_{j=1}^{k} \quad |p_i - p_{ij}| \tag{1}$$

Where $|\cdot|$ represents the Euclidean distance. Then calculate the overall mean $\mu$ and standard deviation $\sigma$ of the average distances of all points, with the calculation formulas as follows:

$$\mu = \frac{1}{n}\sum_{i=1}^{n} d_i \tag{2}$$

$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n} (d_i - \mu)^2} \tag{3}$$

Set the standard deviation multiple threshold n and construct the outlier judgment criterion: when the average distance $d_i$ of the point $p_i$ satisfies $d_i > \mu + n\sigma$, the point is judged as an outlier noise point and eliminated; otherwise, it is retained as a main point. This paper focuses on optimizing two core parameters: the number of neighboring points k and the standard deviation multiple n. By balancing the noise removal effect and the integrity of the main point cloud, it solves the problems of strong subjectivity in parameter setting and insufficient adaptability of the traditional SOR algorithm, and improves the denoising performance of the algorithm for noisy point clouds of large-size components. The experimental results of point cloud denoising obtained based on the optimized SOR denoising algorithm are shown in Fig.2.

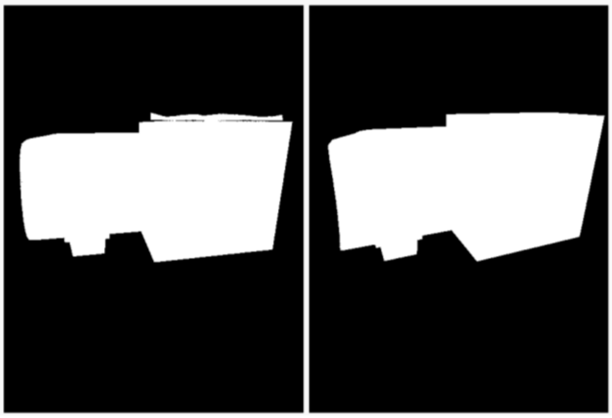

**Figure 2.** Point Cloud Denoising Effect

### 3.2. Point Cloud Registration: RMFD+ICP Fusion Strategy

The point cloud data generated by scanning large-size components has the characteristics of large data volume, obvious feature differences, single surface texture and slowly varying geometric features. Traditional global feature registration methods are prone to misregistration, while local feature registration methods have large computation and long time consumption, making it difficult to balance registration efficiency and accuracy. This paper proposes a Regional Mean Feature Descriptor (RMFD) + Iterative Closest Point (ICP) fusion registration strategy, which realizes fast rough registration through the RMFD algorithm and accurate fine registration through the ICP algorithm, constructing a cooperative registration mechanism of "rough registration for efficiency improvement and fine registration for accuracy guarantee".

The RMFD algorithm balances the retention of local geometric features and computational efficiency by constructing a regional mean feature descriptor of the key point neighborhood, and its core implementation process is as follows: first, extract the key points of the point cloud by using the Intrinsic Shape Signatures (ISS) algorithm to reduce redundant computation; for each key point $p$, construct a neighborhood sphere with $p$ as the center and r as the radius to obtain the neighborhood point set $N(p)$; calculate the centroid $c$ of the neighborhood point set, with the calculation formula as follows:

$$c = \frac{1}{m}\sum_{q \in N(p)} q \tag{4}$$

Where m is the number of points in the neighborhood point set $N(p)$. Perform centralization processing on the neighborhood point set $N(p)$ relative to the centroid $c$ to obtain the centralized neighborhood point set $N'(p) = q - c|q \in N(p)$; perform dimensionality reduction on the centralized neighborhood point set based on the Principal Component Analysis (PCA) algorithm to obtain the principal direction vectors $u_1, u_2, u_3$ and construct a local coordinate system; project the centralized neighborhood point set onto the local coordinate system, calculate the coordinate means $(\mu_x, \mu_y, \mu_z)$, variances $(\sigma_x^2, \sigma_y^2, \sigma_z^2)$ and covariances $(cov_{xy}, cov_{xz}, cov_{yz})$ in the three projection directions, and construct a 9-dimensional RMFD feature descriptor

$$desc(p) = [\mu_x, \mu_y, \mu_z, \sigma_x^2, \sigma_y^2, \sigma_z^2, cov_{xy}, cov_{xz}, cov_{yz}] \quad (5)$$

Calculate the similarity of RMFD feature descriptors of key points of different point clouds, screen the matching points by the ratio of the second nearest distance to the nearest distance, and eliminate mismatched pairs; solve the initial transformation matrix $T = [R, t]$ through the Singular Value Decomposition (SVD) algorithm based on the matching point pairs, where $R \in SO(3)$ is the rotation matrix and $t \in \mathbb{R}^3$ is the translation vector, completing the rough registration of point clouds with a constant time complexity of O(n) to realize the fast alignment of massive point clouds.

The ICP algorithm is used for the fine registration optimization after rough registration, and its core goal is to minimize the corresponding point distance error between two point clouds, constructing the objective function as follows:

$$\min_{R,t} \frac{1}{m} \sum_{i=1}^{m} \quad |q_i - (Rp_i + t)|^2 \quad (6)$$

Where $p_i$ is the point of the source point cloud and $q_i$ is the nearest corresponding point of the target point cloud. The rotation matrix R and translation vector t are solved iteratively, and the transformation parameters are continuously optimized until the error function converges to the set threshold, realizing the accurate registration of point clouds. In this paper, the RMFD rough registration result is introduced as the initial value of the ICP algorithm to avoid the ICP algorithm falling into the local optimal solution, and the corresponding point search strategy is optimized to improve the efficiency of fine registration. Finally, the efficient and accurate registration of low-feature point clouds of large-size components is realized. The experimental results of point cloud registration based on the RMFD+ICP fusion registration strategy proposed in this paper are shown in Figure 3.

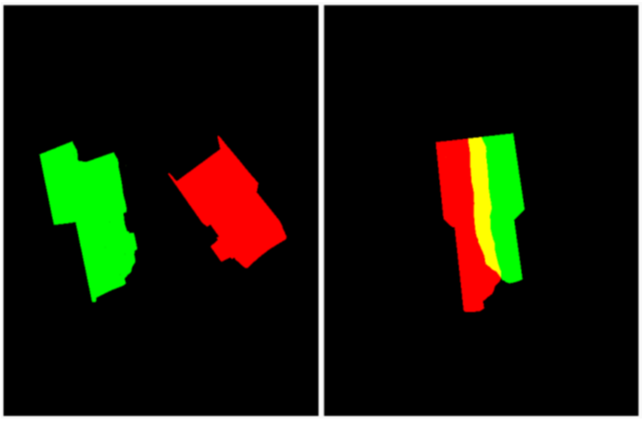

**Figure 3.** Point Cloud Registration Effect

# 4. SUMMARY

Aiming at the technical demand for high-precision and full-coverage 3D scanning of large-size components and the pain points of traditional measurement methods, this paper carries out research on the design of a mobile robot collaborative scanning system, and constructs an overall architecture of "hardware integration - software deployment - process coordination". It completes the hardware selection and integration of the composite robot platform and 3D scanning subsystem, and the construction of the software architecture based on Ubuntu 20.04 and ROS Noetic framework, clarifies the complete technical implementation path of the system, and focuses on optimizing two key algorithms for point cloud data processing - improving the denoising adaptability of the SOR algorithm through parameter optimization, and proposing the RMFD+ICP fusion strategy to solve the problem of balancing the efficiency and accuracy of low-feature point cloud registration. The research improves the specialized integration system for 3D scanning of mobile manipulators and makes up for the shortcomings of existing research. Its hardware integration logic and algorithm theoretical derivation can provide a reference for similar research. In the future, we will further optimize the real-time performance of the algorithm, explore the multi-robot point cloud fusion theory, and improve the theoretical depth and engineering application potential of the research.

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Project Title: Design of a Mobile Robot Collaborative Scanning System for Large-Scale Compo

Project Number:202510066128

Tianjin Science and Technology Program — Cooperation Project between Tianjin and the Chinese Academy of Sciences (CAS)

Project Title: Development of Posture Variation Mechanism and Precision Intelligent Control Technology for Ultra-Minimally Invasive Robotic Puncture Components

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Project Title: R&D of an Embodied Intelligent Mobile Robot Machining and Inspection System for Large-Scale Complex Components

Project Number: 24YFYSHZ00180

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