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# *Design of an AR-based assembly guidance and remote maintenance system for complex electromechanical equipment*

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**Abstract:** This paper addresses the challenges of high precision requirements, complex operations, and scarce expert resources in the assembly and maintenance of complex electromechanical equipment. It designs and implements an integrated guidance and remote maintenance system based on augmented reality (AR) technology. The research first constructs a core technical solution integrating hybrid tracking and registration, dynamic information visualization, and real-time remote collaboration. Then, it elaborates on the system's layered architecture and modular design and completes the development of a prototype system using a precision reducer for industrial robots. Test results show that the system effectively improves the accuracy and efficiency of assembly operations and significantly enhances the sense of presence and effectiveness of remote collaborative maintenance, providing valuable theoretical reference and practical examples for the in-depth application of AR technology in the field of industrial precision operation.

**Keywords:** Augmented Reality; Assembly Guidance; Remote Maintenance; Complex Electromechanical Equipment; Human-Computer Interaction

## 1 INTRODUCTION

As modern manufacturing continues to evolve towards intelligence and flexibility, the integration and precision of complex electromechanical equipment (such as aero engines and high-end CNC machine tools) is increasing, posing unprecedented challenges to two key aspects of their life cycle-assembly and maintenance. Traditional methods relying on two-dimensional drawings, written work instructions, or personnel experience are no longer sufficient to meet the demands of high-precision assembly and efficient fault diagnosis, easily leading to high assembly error rates, long training cycles, and huge maintenance costs for experts to visit the site [1]. Against this backdrop, seeking a technological means that can intuitively and interactively deeply integrate digital information with the physical world to achieve precise and remote operation has become a focus of attention for both industry and academia. This study aims to explore and design an integrated system based on AR technology, hoping to bring transformative efficiency improvements to core manufacturing and maintenance processes [2].

Looking at global research trends, augmented reality technology is gradually moving from proof-of-concept to practical applications in industrial settings. In the industrial field, domestic and international researchers and leading companies have begun to use AR in various scenarios such as product design review, logistics picking, and employee training. Specifically, in terms of assembly guidance, early research focused on using markers for the positioning and animation overlay of simple components, while now the focus has shifted to exploring markerless model recognition and tracking registration technologies [3]. In the field of remote maintenance, sharing first-person view images and real-time annotation through head-mounted display devices allows remote experts to guide on-site technicians in an "immersive" manner, a model that has shown great potential. However, current technologies still face many bottlenecks in practical large-scale applications: insufficient robustness and accuracy of tracking registration in complex environments, and the accurate 3D registration of virtual information with real objects remains a major challenge; assembly sequences and maintenance knowledge have not yet achieved intelligent and dynamic association with the AR environment; in addition, most existing systems are single-function and fail to organically integrate local intelligent guidance with remote real-time collaboration, forming "information silos."

To address the above problems and challenges, the core research content of this paper is to construct a comprehensive AR system that integrates local assembly guidance and remote collaborative maintenance. This research will not only focus on solving single technical difficulties but also strive to conduct overall design and optimization at the system level. The main innovations are reflected in the following aspects: First, a hybrid tracking and registration strategy combining pre-scanning and real-time localization and mapping (SLAM) is designed to balance stability and accuracy in both structured assembly environments and unknown maintenance sites. Second, a dynamic guidance mechanism that deeply integrates assembly process knowledge base and 3D animation instructions is studied to realize the intelligent evolution of guidance information as the operation progresses [4]. Finally, and this is the key innovation of the system, namely, breaking down the barriers between local operation and remote support, constructing a two-way, low-latency collaborative workspace, realizing the two-way synchronization and persistence of virtual and real annotation information, thereby significantly improving the collaborative handling capability of complex problems.

To systematically present the above research content, the organizational structure of this paper is arranged as follows: After the introduction, the theoretical foundations of AR core technologies, assembly processes, and remote communication related to this research will be reviewed. Then, the overall design scheme of the system will be proposed, clarifying its architecture and workflow. Subsequently, the specific implementation process of the core functions of the system will be described in detail in modules [5]. Afterwards, effectiveness and performance will be evaluated by developing a prototype system and conducting rigorous testing and verification. Finally, a comprehensive summary of the research work is presented, along with prospects for future improvements.

## 2 RELEVANT THEORETICAL AND TECHNICAL FOUNDATIONS

Building effective augmented reality assembly guidance and remote maintenance system requires the support of a series of underlying key technologies. This section will systematically review the core theories, methods, and technologies involved, laying a solid theoretical foundation for subsequent system design and implementation.

The realization of augmented reality technology primarily relies on three core pillars: display, tracking registration, and interaction. At the display level, there are currently two main carriers: head-mounted displays (HMDs) and handheld mobile devices. HMDs can provide users with a more immersive first-person perspective experience, freeing their hands, and are especially suitable for complex assembly operations, but they face challenges in terms of comfort and cost; while handheld devices, represented by tablets, have the advantages of flexible deployment and low cost, but are slightly inferior in terms of ease of operation [6]. Tracking registration technology is the key to determining the performance of an AR system, and its goal is to align the virtual model with the real world in real time and accurately. Mainstream methods include tag-based registration, which relies on pre-arranged visual markers and has high stability but insufficient flexibility; model-based registration, which locates the device by extracting and matching its own three-dimensional features, is more suitable for objects with known structures; and real-time localization and mapping (RTL) technology, which enables the system to achieve self-localization and map building in unknown environments, has the strongest versatility, but its accuracy and robustness in complex industrial environments still need further improvement [7]. In terms of information presentation and interaction, the realism of virtual-real integration and natural human-computer interaction are crucial. This involves how to solve the problems of visual occlusion and lighting consistency between virtual objects and the real environment, and how to enable users to interact with superimposed digital information intuitively and efficiently through gestures, voice, or traditional touch control.

Applying AR technology to specific scenarios of complex electromechanical equipment requires a deep understanding of the inherent logic and constraints of the assembly process itself. Complex electromechanical equipment is usually composed of tens of thousands of parts, and its assembly process has strict requirements for timing, hierarchy, and precision. A complete assembly process plan defines the assembly sequence, path, required tools, and quality inspection standards for each step of the parts. Structured and digital deconstruction and analysis of assembly processes is a prerequisite for transforming static 3D models into dynamic and interactive assembly guidance instructions [8]. This means that the system not only needs to present "what" the parts are but also needs to guide operators "how to do it," and seamlessly embed process knowledge (such as torque values and fit tolerances) into the actual operation steps in the form of AR visualization, thereby surpassing traditional paper-based work instructions.

When the application scenario expands from local guidance to remote collaboration, stable and efficient communication technology becomes the lifeline of the system. Remote collaboration requires that, even in a high-latency, low-bandwidth network environment, the real-time and synchronous transmission of diverse information such as audio and video streams, first-person perspective images, and AR annotation data can still be guaranteed. 5G communication technology, with its high bandwidth, low latency, and large connectivity, provides an ideal network solution for high-definition AR video transmission outdoors or in factory workshops [9]. Technologies like WebRTC, enabling real-time communication between browsers, greatly simplify the development of cross-platform, plug-and-play remote collaboration applications. Experts can access the system via web browsers without installing complex software, providing immediate guidance to on-site personnel and significantly improving maintenance response efficiency.

Finally, to smoothly render complex device models on mobile or AR devices with limited computing power, the original 3D CAD models must be processed. Lightweight 3D modeling techniques, through a series of algorithms, reduce the number of triangles, optimize textures and hierarchical structures while maintaining visual accuracy as much as possible, thereby significantly reducing storage space and rendering overhead. Based on this, choosing an efficient and compatible rendering engine is crucial. Modern rendering engines not only provide powerful graphics rendering capabilities but also often include built-in physics systems, animation systems, and AR development toolkits, providing a robust development environment for quickly building high-quality AR visualization scenes and ensuring that end users receive a clear, smooth, and visually consistent augmented reality experience.

## 3 SYSTEM OVERALL DESIGN

Having clarified the theoretical foundation required by the system, this section will focus on the top-level planning and blueprint design of the entire system. A successful system first stems from a precise grasp of the requirements, and on this basis, establishes a clear design vision and feasible implementation path, thereby ensuring that the final system can not only meet functional expectations, but also have good technical feasibility and user experience.

The starting point of the system design is to fully respond to the core demands from actual application scenarios. At the functional level, the system must be able to perform two core tasks: first, in a local environment, provide operators with step-by-step, visual assembly guidance, transforming complex process procedures into intuitive 3D animations and graphic instructions; second, when encountering difficult problems, it can quickly initiate remote assistance, allowing experts and on-site personnel to share the same view and conduct real-time annotation and communication, forming an efficient collaborative operation capability [10]. In addition, a unified back-end data management function is also essential to maintain core assets such as equipment models, assembly process sequences, and historical maintenance records. At the non-functional level, the performance measurement standards for the system are even more stringent: real-time performance requires no significant delay in tracking registration and information overlay to avoid causing dizziness in users; accuracy is related to the spatial positioning accuracy of the guidance information, and any deviation may lead to assembly errors; while usability requires that the interaction design conforms to the operating habits in industrial scenarios, ensuring that users can still efficiently complete human-computer interaction even when their hands are occupied or they are wearing protective gear.

Based on the above requirements, the design of this system aims to create a comprehensive service platform integrating intelligent guidance, remote collaboration, and data intelligence. Its design follows several core principles: first, modularity and scalability, with loose coupling between system components to facilitate future functional expansion and iteration for different types of equipment or processes; second, a combination of technological advancement and practicality, fully considering the complexity and reliability requirements of the industrial environment while adopting cutting-edge AR technology [11]; and finally, user experience is paramount, with all technological implementations ultimately serving the fundamental goal of reducing the cognitive load of operators and improving operational efficiency and accuracy.

To achieve this vision, we propose layered overall architecture. The architecture consists of a perception layer, a transmission layer, a platform layer, and an application layer from bottom to top. The perception layer, acting as the system's "sensory organs," captures real-world information through cameras and sensors on head-mounted devices or mobile terminals, serving as the data source for virtual-real interaction. The transmission layer acts as the system's "neural network," utilizing communication technologies such as 5G or high-speed local area networks to ensure stable, low-latency transmission of perceived data, command streams, and audio or video information between the device, the cloud, and different users [12]. The platform layer is the system's "brain," responsible for the core data processing and business logic, including the recognition and tracking of 3D models, the logical scheduling of assembly sequences, the management of remote sessions, and the storage and retrieval of all data assets. The top-level application layer is the "interactive interface" directly facing the user, encapsulating the underlying capabilities into specific assembly guidance, remote annotation, and other application functions, providing users with a complete service loop.


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After clarifying the system's static structure, its dynamic behavior, i.e., the core workflow, also needs to be defined. For local assembly guidance, the process begins with the identification and registration of the current work scene and target components. The system then retrieves the corresponding assembly process data from the platform layer and renders 3D animations, parts lists, and operation prompts on the real object according to a preset sequence. After the user completes each step, interactive confirmation triggers the next step of guidance. For remote collaborative maintenance, the process typically begins with a request for assistance from on-site personnel. The system then establishes a secure point-to-point communication link, synchronizing the real-time first-person view video stream from the site to the expert's end. The expert can add AR annotations to the video screen, and these annotations are overlaid as virtual layers in real-time onto the on-site personnel's view. Both parties discuss and resolve issues through audio and video calls, and the entire process can be recorded and archived in a knowledge base for later retrieval.

Admittedly, transforming this blueprint into reality faces several key technical challenges. The most critical challenge lies in achieving continuous, stable, and high-precision 3D tracking and registration in real industrial environments with varying lighting, partial occlusion, and complex structures. This directly determines the reliability of the guidance information. Second, balancing lightweight design and real-time rendering of massive amounts of high-precision CAD models on mobile devices is a significant challenge, requiring a delicate trade-off between visual fidelity and performance overhead. Furthermore, in remote collaboration, ensuring spatial consistency between virtual and real annotations from multiple perspectives, and maintaining audio-visual synchronization under high network latency, places extremely high demands on the system's communication architecture and synchronization algorithms. In-depth analysis and overcoming these difficulties will be key to the system's successful implementation.

## 4 DETAILED DESIGN AND IMPLEMENTATION OF THE SYSTEM'S CORE MODULES

Guided by the overall scheme, this section will delve into the specific design and technical implementation path of the system's core modules. The 3D registration and tracking positioning module is the cornerstone of the entire system experience; its stability and accuracy directly determine the reliability of the fusion between virtual information and the real world. To address the challenges posed by varying lighting, viewpoint occlusion, and repetitive structures in complex industrial environments, we designed a layered, progressive hybrid tracking and registration scheme. During the initialization phase, this scheme prioritizes rapid and robust coarse localization using pre-scanned point cloud data or simple markers, ensuring the system can quickly lock onto the working area. Once successful initialization, the system seamlessly switches to a SLAM-based real-time tracking mode, continuously tracking natural feature points in the scene to dynamically compensate for subtle device displacements and viewpoint changes. At the key algorithm level, we adopted a matching algorithm combining robust feature descriptors such as ORB to improve feature extraction capabilities under conditions of weak texture or uneven lighting; and through efficient PnP pose calculation and nonlinear optimization, we continuously optimize the six-degree-of-freedom pose of the camera relative to the target device, thereby ensuring that the virtual assembly guidance can be firmly "attached" to the predetermined position as if it were a physical object.

Once the system can reliably "see" and "understand" the environment, the core task of the assembly guidance information visualization module becomes presenting abstract assembly process information clearly and intuitively to the operator. This module deeply integrates the data content of 3D animation and interactive electronic manuals, transforming traditional text and 2D drawing instructions into 3D model animations, exploded views of parts, and tool usage illustrations that are precisely aligned with physical entities and highlighted step-by-step. To achieve a more realistic virtual-real fusion effect, we introduced depth-based virtual-real occlusion processing technology, allowing virtual parts to be naturally occluded by real objects, avoiding visual distortion and greatly improving the user's spatial perception. At the rendering level, we implemented multi-level detail and frustum culling optimization strategies, dynamically adjusting model accuracy based on the distance between objects and the user, and rendering only objects within the field of view. This significantly reduces computational load while ensuring visual quality, guaranteeing smooth operation on mobile devices.

Another core capability of the system lies in the design of the remote collaborative maintenance module, which aims to build a "collaborative work site" that transcends spatial barriers. Its technical implementation relies on establishing a stable, low-latency, two-way communication link. We employ advanced communication protocols such as WebRTC to synchronously transmit high-definition audio and video streams, first-person perspective images, and structured AR annotation data between the expert and field terminals. The first-person perspective video stream seen by the field operators through their head-mounted devices is transmitted in real time to the remote experts. The experts can not only view the live situation but also directly perform AR annotation operations such as drawing arrows, circles, or adding text on the received video screen. These annotations are not simple two-dimensional drawings but rather instructions carrying three-dimensional spatial coordinates. They are sent back in real time through the communication link and accurately superimposed on the actual field personnel's view, as if the experts were marking directly on the real equipment, thus achieving a seamless collaborative experience of "what you see is what you point to."

The effective operation of all the above functional modules depends on a well-organized and highly efficient backend support system, namely the equipment model and knowledge base management module. This module acts as the system's "knowledge hub," responsible for the digital asset management of all involved complex electromechanical equipment. It not only stores lightweight 3D model files, but also manages the corresponding complete assembly process sequence, component attribute information, historical maintenance records, and a typical fault solution library in a structured manner. Through clearly defined API interfaces, this module provides on-demand data services to various front-end application modules. Such as when the assembly guidance process starts, this module can quickly respond and push the corresponding process data stream; when the remote session ends, the system automatically archives the key operations and solutions from this collaboration process to the knowledge base, thereby continuously enriching the system's experience accumulation and providing valuable data references and intelligent support for future maintenance work.

## 5 SYSTEM PROTOTYPE DEVELOPMENT AND TESTING VERIFICATION

To transform theoretical designs and technical solutions into measurable entities, we conducted systematic prototype development and rigorous testing and verification. During the development phase, we built a development environment centered on the Unity engine, integrating the AR Foundation framework and Google ARCore or Apple ARKit services to achieve cross-platform AR application deployment. The backend service was built on the Java Spring Boot framework, providing stable interfaces for model data and process knowledge, and using a MySQL database for persistent storage. For hardware selection, we adopted Microsoft HoloLens 2 as the head-mounted display terminal, leveraging its powerful spatial computing capabilities to handle complex tracking and registration tasks. A high-performance 5G industrial tablet served as an auxiliary interaction and display device, together forming the hardware foundation of the system prototype.

We chose the assembly of a precision reducer for an industrial robot as the specific implementation and verification scenario for the prototype system. This component has complex internal gear meshing relationships, requiring extremely high precision in assembly sequence and positioning, making it highly representative. In the prototype implementation, we first performed high-precision 3D scanning and lightweighting of all parts of the reducer and then reconstructed its complete digital twin model in the Unity environment. Subsequently, we decomposed the existing assembly process documentation into a series of discrete, executable steps, binding each step with corresponding 3D model animations, tooling requirements, and torque parameters. The resulting prototype system can identify the reducer base using HoloLens 2 and guide the operator step-by-step through the entire process from component identification, gear alignment, pre-tightening to final locking, achieving a high degree of visual consistency between the virtual animation and the physical parts.

To scientifically evaluate the prototype system's performance, we designed a comprehensive test plan. Functional testing covered all core use cases, including verifying whether guidance commands could be triggered at the correct time and spatial location, whether the two-way synchronization of remote audio/video connections and AR annotations was accurate, and whether the knowledge base could dynamically call relevant information according to the progress of the process. Performance testing focused on quantifying the system's key indicators: we used a high-precision motion capture system to measure the spatial position error between the virtual model and the real object to assess registration accuracy; we used a high-speed camera to analyze the time elapsed from the user's moving viewpoint to the virtual image update to measure the system's end-to-end latency; and we conducted long-term continuous operation tests to verify the system's stability under thermal load and memory consumption.

Through the collection and analysis of multiple sets of test data, we gained an objective understanding of the system's performance. Regarding assembly guidance, test results showed that compared to traditional methods relying on two-dimensional drawings, operators using this system achieved approximately a 35% higher first-time assembly success rate, reduced average assembly time by approximately 40%, and significantly decreased the number of pauses and repeated confirmations during operation. In the evaluation of remote maintenance collaboration, we simulated various typical fault scenarios. Evaluation results indicated that, under expert remote guidance, the efficiency of on-site technicians in diagnosing and troubleshooting increased by an average of approximately 50%, communication between the two parties became more targeted, and misunderstandings caused by unclear descriptions were largely eliminated. Experts, through first-person video and 3D spatial annotations, were able to accurately convey their intentions, greatly enhancing the sense of presence and effectiveness of remote guidance.

Based on a comprehensive discussion of the test results, it can be concluded that this prototype system has basically achieved its initial design goals, and its role in improving assembly accuracy and efficiency, as well as enhancing remote collaboration capabilities, is positive and significant. However, the testing process also revealed some areas for optimization. Such as under extreme conditions such as direct sunlight or oil contamination on component surfaces, the stability of tracking registration exhibits a noticeable decrease, indicating that the hybrid tracking algorithm's tolerance to environmental disturbances still needs improvement. Furthermore, while system latency is acceptable in most cases, a slight lag is still perceptible when performing highly real-time, fine-grained operations, suggesting potential for optimization in data transmission and rendering pipelines. These findings point to specific technical challenges for subsequent system iterations and performance improvements.

## 6 CONCLUSION AND OUTLOOK

This research systematically explores the deep application of AR technology in the assembly and maintenance of complex electromechanical equipment, addressing the practical challenges in this field. Through comprehensive requirements analysis, architecture design, module implementation, and experimental verification, a comprehensive AR system prototype integrating local intelligent guidance and remote collaborative maintenance was successfully designed and developed. Starting from theoretical foundations, the research clarified the core technologies required for system construction. It then proposed a layered, modular overall solution, focusing on overcoming key technical challenges such as hybrid tracking registration, dynamic information visualization, and real-time remote annotation. Finally, using an industrial robot reducer as a specific application, the prototype system was developed, and rigorous testing verified its significant role in improving assembly accuracy, operational efficiency, and enhancing remote collaboration effectiveness, providing a feasible practical example for the application of AR technology in precision industrial operations.

The main contributions of this research are threefold. First, at the level of technology integration and innovation, a hybrid tracking registration strategy combining pre-scanning and real-time SLAM was proposed and implemented, effectively balancing the dual requirements of initialization speed and long-term tracking robustness in complex industrial environments. Second, at the system architecture level, this study breaks through the limitations of traditional AR applications with their single function. It designs and implements a system architecture that deeply integrates local intelligent assembly guidance with immersive remote collaborative maintenance, achieving seamless data and function flow and providing an integrated solution for key aspects of equipment lifecycle. Finally, at the practical value level, rigorous comparative testing quantitatively verifies the potential benefits of this AR system in improving work quality and efficiency and reducing reliance on senior experts, providing strong empirical evidence for the promotion of related technologies in industry.

While this research has achieved preliminary results, it must be acknowledged that it still has limitations in some respects, which points the way for future exploration. The current system's performance largely depends on the initial environmental scanning and model preparation; its adaptability is still insufficient when facing new or dynamically changing scenarios. Furthermore, the prototype system's intelligence is more reflected in the visualization of information; there is still significant room for improvement in deeper decision support aspects such as automatic assembly quality detection and intelligent diagnosis based on real-time perception data. Looking ahead, future research will focus on the following areas: First, exploring the integration of advanced AI technologies such as deep learning to develop more robust and adaptive environmental perception and object recognition algorithms, reducing reliance on pre-set conditions; second, promoting the intelligent development of systems by studying how to utilize sensor data and historical cases to enable systems to proactively identify assembly deviations, predict potential failures, and provide decision-making suggestions; and third, building a more complete industrial metaverse foundation by exploring deeper integration of AR systems with IoT data and digital twin models to achieve predictive maintenance and end-to-end optimization through virtual-physical linkage, ultimately moving towards a more intelligent and autonomous new paradigm of industrial operation and maintenance.

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