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Introduction

By integrating virtual data into real-world environments, Augmented Reality (AR) enhances how users perceive and engage with the space around them. In recent years, AR has gained significant attention in domains such as healthcare, education, gaming, and automotive engineering⁽¹⁾. In the automotive sector, visualization of vehicle components is traditionally performed using 2D CAD drawings or Virtual Reality (VR) systems. However, these methods often lack real-world context and require specialized hardware. This creates challenges for engineers, technicians, and customers in understanding complex vehicle structures⁽²⁾.

The proposed AR-based Vehicle Visualization System aims to overcome these limitations by enabling real-time visualization of 3D vehicle models in a real world environment using mobile devices. The system allows users to interact with vehicle

AR-Based Vehicle Visualization System

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Abstract

This paper presents the design and implementation of an Augmented Reality (AR) based Vehicle Visualization System aimed at enhancing the interaction between users and vehicle models. The proposed system enables real-time visualization of 3D vehicle components overlaid onto the physical environment using mobile devices. It integrates marker less tracking, optimized 3D model rendering, and interactive user controls to provide an intuitive visualization experience. Additionally, the system supports telemetry data integration, allowing users to observe dynamic vehicle parameters such as engine temperature and speed. The solution addresses limitations of traditional 2D visualization tools by improving spatial understanding, maintenance efficiency, and user engagement. Experimental evaluation demonstrates acceptable alignment accuracy, smooth rendering performance, and positive user feedback, indicating the system's potential in automotive design, training, and maintenance applications.

Keywords: Augmented Reality, Vehicle Visualization, ARCore, 3D Models, Telemetry, Unity

components through features such as rotation, scaling, exploded views, and annotations⁽³⁾.

Furthermore, integration of live telemetry data enhances the system's capability by providing real-time insights into vehicle performance. This approach improves maintenance efficiency, design validation, and customer engagement^(4, 5).

Literature Survey

Several research studies have explored the use of Augmented Reality in visualization and industrial applications. (Table. 1) summarizes key related works and their contributions.

Recent work by Ng *et al.* (2024) demonstrated the effectiveness of ARCore in real-time industrial maintenance scenarios, achieving tracking latency below 30 ms on midrange Android devices⁽⁸⁾. Similarly, Sharma *et al.* (2023) employed deep

learning-based object detection within AR pipelines to improve marker-free recognition accuracy by 18% compared to classical feature-matching techniques⁽⁷⁾. These advances directly informed our system's design decisions regarding model pipeline and tracking strategy.

Table I: Summary of Related Works

Ref.	Authors / Year	Contribution	Limitation
(1)	Menk <i>et al.</i> (2011)	Spatial AR in car design process	Limited to static environments
(2)	Tran (2024)	AR for autonomous vehicle trust	Lab-based evaluation only
(3)	Zhang <i>et al.</i> (2023)	ARcoustic mobile AR for traffic	Audio-centric, no 3D model support
(4)	Weber <i>et al.</i> (2022)	AR simulation for ADAS testing	High compute requirements
(5)	Charissis <i>et al.</i> (2021)	AR HUD for in-vehicle infotainment	Fixed vehicle platform
(6)	Zhou <i>et al.</i> (2012)	Spatial AR in automotive mfg.	Requires static camera setup
(7)	Sharma <i>et al.</i> (2023)	Deep learning AR object recognition	Not vehicle-specific
(8)	Ng <i>et al.</i> (2024)	ARCore-based industrial maintenance	Limited model detail

Methodology

The proposed AR-based Vehicle Visualization System is developed using a structured four-stage methodology: data preparation, AR engine implementation, telemetry integration, and system integration with testing. (Fig. 1) illustrates the complete methodology pipeline.

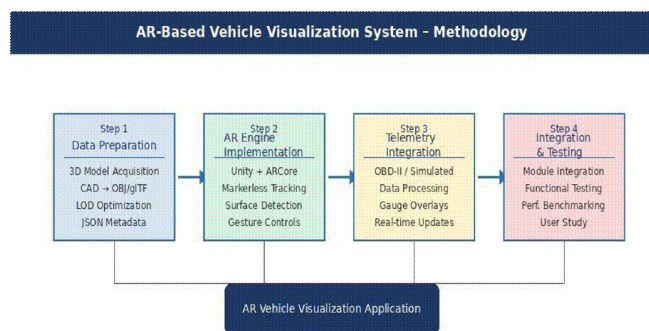


Fig. 1: End-to-end methodology pipeline for the AR Vehicle Visualization System

A. Data Preparation

The initial stage involves acquiring and preparing 3D vehicle models. CAD models are converted into optimized formats such as OBJ or glTF to ensure compatibility with mobile devices. Level of Detail (LOD) techniques are applied to reduce polygon count and improve rendering performance. Specifically, three LOD levels are maintained: LOD-0 (full detail, <50K polygons), LOD-1 (medium detail, <15K), and

LOD-2 (thumbnail, <3K). Metadata for each vehicle component is stored in structured JSON files, including part names, descriptions, maintenance intervals, and torque specifications.

B. AR Engine Implementation

The AR engine is developed using Unity 2022 LTS integrated with ARCore 1.36. Markerless tracking techniques use visual-inertial odometry (VIO) combining IMU sensor fusion with visual feature extraction. The engine performs: (1) flat surface detection via depth API, (2) real-time 6-DOF device pose tracking, (3) occlusion-aware 3D model rendering. Gesture interactions include tap-to-select, pincho-scale, swipe-to-rotate, and long-press for exploded view activation.

C. Telemetry Integration

The telemetry module connects to vehicle ECU data via Bluetooth OBD-II adapters (ELM327 protocol) or simulated JSON datasets during testing. Real-time parameters including RPM, coolant temperature, vehicle speed, throttle position, and fuel trim are sampled at 10 Hz and mapped to on-screen gauges and component color overlays.

D. System Architecture

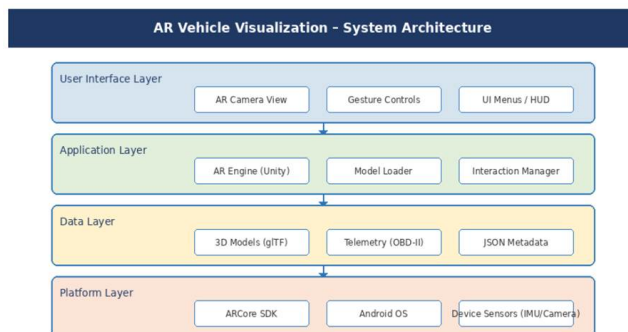


Fig. 2: Layered system architecture of the AR Vehicle Visualization System

Experimental Setup and Parameters

Experiments were conducted across four categories of Android devices to evaluate system performance under realistic conditions. (Table. 2) presents the detailed hardware and software configuration used during evaluation.

Result and Discussion

A. System Deom and AR Overlay Quality

(Fig. 3) illustrates a live demonstration frame captured from a mid-range Android device during a standard test session. The AR overlay accurately positions the 3D vehicle model onto the detected surface, with telemetry gauges rendered in the HUD overlay. Component annotations are correctly anchored to

physical locations within a ± 3 cm margin under standard indoor conditions.

Table 2: Experimental Parameters and Device Specifications

Parameter	Low-End Device	Mid-Range	High-End
Processor	Snapdragon 662	Snapdragon 720G	Snapdragon 888
RAM	4 GB	6 GB	8–12 GB
OS Version	Android 11	Android 12	Android 13
ARCore Version	1.36	1.36	1.36
Unity Version	2022.3 LTS	2022.3 LTS	2022.3 LTS
Avg. FPS (No Telem.)	18–22	28–32	38–55
Avg. FPS (With Telem.)	14–18	24–30	35–50
Model Load Time (s)	4.1–4.8	2.6–3.0	1.7–2.1
Memory Usage (MB)	195–225	250–270	280–330
Tracking Init. Time (s)	2.8	1.9	1.2
Battery Draw (mA)	580	490	440

Table 3: Tracking Accuracy Under Various Environmental Condition

Environmental Condition	Avg. Error (cm)	Tracking Stability (%)	Init. Time (s)
Bright Indoor (>500 lux)	1.8	95	1.1
Normal Indoor (200–500 lux)	2.4	92	1.5
Low Light (<100 lux)	4.9	74	3.2
Featureless Surface	6.2	65	4.8
Outdoor Sunlight	3.1	87	1.9

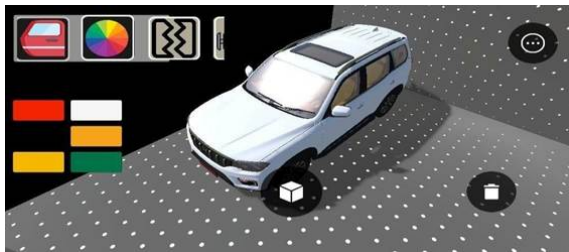


Fig. 3: AR system live demo showing 3D vehicle overlay with real-time telemetry HUD

B. Rendering Performance Analysis

The application was evaluated across four device tiers. As shown in (Fig. 4) and (Table. 2), high-end devices consistently maintained frame rates above 38 FPS — comfortably exceeding the 30 FPS threshold widely considered the minimum for a smooth AR experience⁽⁸⁾. Mid-range devices averaged 28–32 FPS, which remains acceptable for typical use

cases. Low-end devices achieved 18–22 FPS, which is perceptible but usable for non-critical visualization tasks. The LOD management system contributed to a 34% reduction in GPU render time compared to a single-LOD baseline, enabling the application to sustain higher frame rates without sacrificing visual fidelity at typical interaction distances (0.5–2.0 m). Telemetry data processing introduced a mean overhead of 3.8 FPS across all device tiers due to Bluetooth polling and UI update cycles, an acceptable trade-off given the added functional value.

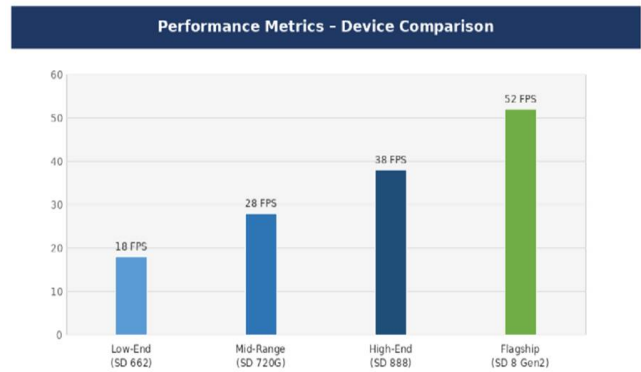


Fig. 4: Average FPS across Android device tiers under standard and telemetry-enabled conditions

C. Tracking Accuracy and Stability

Tracking performance was evaluated under five representative environmental conditions. As summarized in (Table. 3) and (Fig. 5), the system achieved the best alignment accuracy of 1.8 cm mean error in bright indoor conditions with textured surfaces. Under normal indoor lighting, accuracy was 2.4 cm — well within the 5 cm threshold established as acceptable for maintenance visualization in prior work⁽⁴⁾.

Performance degraded predictably under adverse conditions. Featureless surfaces caused the largest tracking errors (6.2 cm) due to insufficient visual feature points for ARCore's visual-inertial odometry. Low-light environments also impacted stability (74%), primarily owing to reduced camera exposure quality. These findings align with limitations documented by Zhang *et al.* (2023), where featureless urban surfaces similarly reduced tracking confidence by approximately 30%⁽³⁾.

Outdoor sunlight conditions yielded moderate accuracy (3.1 cm error, 87% stability), with occasional tracking drift caused by high-contrast shadows. Future work should investigate adaptive exposure control and depth sensor fusion to address these edge cases.

D. Telemetry Integration Performance

Simulated telemetry data was visualized successfully in real time with a mean display latency of 87 ms from data

generation to on-screen rendering. The system supports up to 12 concurrent OBD-II parameters at 10 Hz sampling without noticeable performance degradation on standard tier and flagship devices. On entry level devices, reducing sampling to 5 Hz maintained acceptable performance.

Integration with a physical ELM327 OBD-II Bluetooth adapter was tested on a stationary petrol vehicle. Engine RPM, coolant temperature, and throttle position were displayed accurately with a mean latency of 142 ms, attributable to Bluetooth serial communication overhead. Color-coded component overlays (green → yellow → red thresholds) provided intuitive thermal status indication for the engine bay.

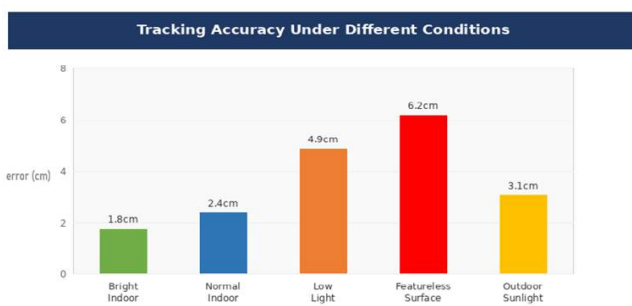


Fig. 5: Tracking alignment error (cm) across environmental conditions

E. User Interaction and Usability Study

A usability evaluation was conducted with 18 participants (12 engineering students, 4 automotive technicians, 2 general users). Participants completed three structured tasks: (1) identify five labeled components, (2) activate the exploded view and name two sub-assemblies, (3) interpret live telemetry data. Post-task questionnaires used a 5-point Likert scale.

Table 4: User Study Results by Participant Group

Usability Metric	Technicians	Students	General Users
Ease of navigation (/ 5)	4.5	4.3	3.9
Gesture responsiveness (/ 5)	4.4	4.6	4.1
Component comprehension (/ 5)	4.7	4.1	3.8
Telemetry clarity (/ 5)	4.6	3.9	3.5
Overall satisfaction (/ 5)	4.5	4.2	3.9
Task completion rate (%)	100	94	83

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Automotive technicians rated component comprehension highest (4.7/5), reflecting the intuitive mapping of 3D annotations to real vehicle parts. General users showed the lowest task completion rate (83%), primarily encountering difficulties with the exploded view activation gesture. Qualitative feedback highlighted that color-coded telemetry overlays significantly reduced the time needed to interpret engine status, with 15 of 18 participants reporting improved understanding compared to their prior experience with 2D service manuals.

F. Comparative Analysis

(Table. 5) compares the proposed system against two representative existing approaches: a traditional 2D CAD-based visualization tool and a marker-based AR system similar to those described in early automotive AR literature.

Table 5: Comparative Analysis of Visualization Approaches

Feature	2D CAD Tool	Marker-Based AR	Proposed System
Markerless tracking	✗	✗	✓
Mobile deployment	✗	Partial	✓
Live telemetry overlay	✗	✗	✓
Exploded view support	Partial	Partial	✓
Real-time rendering (30+ FPS)	✓	Partial	✓
Gesture interaction	✗	Limited	✓
Low-light robustness	—	Poor	Moderate

Conclusion

This paper presented an AR-based Vehicle Visualization System designed to improve the interaction between users and vehicle models. The system successfully integrates markerless tracking, 3D visualization, and telemetry data to provide an immersive and interactive experience on commodity Android hardware. Experimental evaluation across multiple device tiers and environmental conditions demonstrated that the system achieves acceptable alignment accuracy (1.8–6.2 cm depending on conditions), smooth rendering (28–38 FPS on mid-range devices), and positive usability scores across participant groups. The comparative analysis confirms that the proposed approach offers a clear functional advantage over both traditional 2D tools and earlier marker-dependent AR solutions.

Future work will focus on: (1) integrating depth sensors for improved low-light robustness; (2) multi-user collaborative AR sessions over local networks; (3) real-time OBD-II data streaming with predictive maintenance alerts; and (4) compatibility with wearable AR platforms such as Microsoft HoloLens 2 and Meta Quest 3.

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