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# Lightweight Mobile AR for Crane Safety Education: Dual-Mode 3D Visualization to Enhance Load-Chart Interpretation and Spatial Awareness

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***Abstract*— Mobile crane operations are among the most hazardous activities in construction, and effective safety planning often hinges on a practitioner's ability to infer complex three-dimensional relationships from static two-dimensional load charts and schematic diagrams. This study reports the development and preliminary evaluation of AR Crane Safety Viewer, a low-resource mobile augmented reality application designed to reduce this interpretive burden in crane safety education. Implemented in Unity 2022.3 LTS using AR Foundation and ARCore, the system adopts a dual-mode workflow consisting of a stable 3D viewer for controlled conceptual inspection and a markerless AR mode that enables contextual placement of the crane model on real-world surfaces. The application embeds on-model annotations to externalize key geometric parameters boom angle, boom length, load radius, and lifting height thereby supporting learner understanding of the crane working envelope through interactive exploration rather than memorization. In contrast to high-fidelity simulators that demand specialized hardware and high computational resources, the proposed tool targets mid-range Android devices to facilitate deployment in classrooms and pre-task briefings. The architecture prioritizes consistency of interface and interaction across modes, incorporating drag-based rotation, pinch-to-zoom scaling, and optional auto-rotation for hands-free demonstration, alongside an integrated screenshot workflow to support documentation. Functional testing on a Samsung M33 5G indicates reliable operation of both viewing and AR placement features under typical indoor conditions. Collectively, these results suggest that lightweight interactive 3D visualization combined with contextual AR placement can strengthen pre-lift awareness and improve comprehension of safety-critical crane terminology. The study contributes an implementable design pattern for accessible AR-enabled learning tools in construction safety training and provides a basis for subsequent controlled studies quantifying learning gains and error reduction in load-chart interpretation.**

***Keywords*—Augmented Reality, ARCore, Safety Training, Crane Geometry, 3D Visualization**

## I. Introduction

The construction industry remains one of the most hazardous sectors globally, with crane-related incidents consistently ranking among the leading causes of fatalities and severe property damage. Safe crane operation is not merely a matter of mechanical skill but is deeply rooted in the rigorous planning of the lifting envelope, which requires an expert-level understanding of load dynamics and spatial constraints. In modern construction management, the "pre-lift briefing" is a critical safety intervention where operators and riggers must align their mental models of the crane's configuration relative to site hazards. However, a persistent challenge in both academic training and professional development is the reliance on 2D abstractions such as radius-load charts and static diagrams to communicate 3D spatial risks. These traditional methods often fail to convey the dynamic relationship between boom configuration and the effective load radius, leading to cognitive "blind spots" where trainees memorize technical terms without grasping their physical implications. This lack of spatial intuition is a primary factor in accidents involving tip-overs, structural failures, and collisions with power lines or surrounding structures.

Recent advancements in spatial computing, specifically Augmented Reality (AR), offer a transformative opportunity to address these pedagogical limitations by overlaying digital information onto the physical world. While high-end Virtual Reality (VR) simulators provide immersive experiences, they are often hindered by high implementation costs, the need for specialized hardware, and a "tethered" experience that is difficult to replicate in a dynamic classroom or site office setting. There is a growing demand for "low-resource" AR solutions applications that can run on standard consumer-grade mobile devices without the need for sophisticated depth sensors or external markers.

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This research addresses this gap by introducing a Mobile Crane AR Safety Viewer that prioritizes conceptual clarity and accessibility over high-fidelity physics simulation. By utilizing markerless plane detection through ARCore, the application allows users to project life-sized or scaled crane models onto any flat surface, transforming a desk or a construction yard into an interactive learning laboratory. The core motivation is to provide a "pre-lift awareness" tool that simplifies the visualization of safety-critical parameters, thereby enhancing the user's ability to interpret professional safety resources, such as load charts and site plans, with greater accuracy.

The objective of this paper is to detail the design, architecture, and implementation of a dual-mode AR application specifically tailored for crane geometry education. The study contributes to the field in three distinct ways. First, it proposes a unified UI framework that maintains consistency between a non-AR 3D viewer and an AR environment, reducing the cognitive load on the user during the learning process. Second, it demonstrates the integration of "on-model annotations" that serve as persistent visual anchors for key terms like "centre of rotation" and "reach," which are frequently misunderstood in 2D formats. Third, it provides a workflow for "documentation-based learning," where students can capture and report 3D configurations, thereby reinforcing their understanding through active synthesis. By focusing on a "lightweight" deployment strategy, this work shows that meaningful safety improvements can be achieved through accessible technology, providing a scalable model for broader equipment safety training in the AEC (Architecture, Engineering, and Construction) industry. The following sections will detail the system's development in Unity, its interaction logic, and a case study demonstrating its application in a controlled educational environment.

## II. Literature Review

The integration of immersive technologies in construction safety management has undergone a significant paradigm shift over the last decade, moving from experimental prototypes to indispensable pedagogical tools [1]. Previous studies consistently highlight that construction sites are dynamic environments where traditional 2D safety training often fails to prepare workers for 3D spatial hazards [2]. Cranes, in particular, represent a critical area of concern; industry research emphasizes that a correct understanding of load charts, operating radii, and ground conditions is frequently missing among early-stage practitioners.

This cognitive gap is often attributed to the "abstraction penalty," where learners struggle to translate flat diagrams into the complex 3D mental models required to judge reach and clearance in real-time. Consequently, researchers have turned to Augmented Reality (AR) and Virtual Reality (VR) to increase engagement and provide repeatable practice in visualizing hazards that are otherwise difficult to communicate through text alone.

While VR has been praised for its total immersion, AR is increasingly recognized as a more suitable candidate for field-adjacent learning because it overlays digital content directly onto the physical environment, supporting contextual understanding without disconnecting the user from the construction site. Early AR applications in construction primarily focused on marker-based systems, which required physical printouts to trigger digital overlays [3]. However, recent advancements in markerless AR, supported by frameworks like ARCore and AR Foundation, have enabled more flexible deployment. These systems utilize "Plane Detection" to understand the geometry of the physical world, allowing 3D models to be placed on any flat surface. Despite these technical leaps, many existing AR safety tools remain "heavy," requiring high-end mobile devices with depth sensors or LIDAR capabilities [4]. This creates a barrier to entry for educational institutions or firms with limited resources, necessitating the development of "low-resource" applications that can run smoothly on mid-range Android hardware.

The specific application of AR to crane safety has traditionally focused on high-fidelity operator simulators designed to mimic the exact controls of a crane cabin [5]. While effective for technical skill acquisition, these simulators often overlook the "conceptual awareness" needed by non-operators such as riggers, site supervisors, and safety inspectors who must understand the crane's working envelope from the ground. Research in construction education suggests that interactive visualization significantly improves the comprehension of spatial relationships and task sequencing. By enabling users to directly manipulate a crane model and observe labeled parameters, AR can reduce the cognitive load associated with learning abstract safety rules. This "pre-lift awareness" is a foundational requirement for safe practice, strengthening the user's mental model before they encounter real-world site operations.

Current gaps in the literature suggest a need for a unified "Dual-Mode" approach that combines the stability of a 3D viewer with the spatial context of AR. Most current tools provide either a static 3D model or a pure AR experience, often lacking structured instructional content or a consistent user interface (UI).

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Furthermore, the transition between learning a concept in a controlled environment and applying it in a real-world context is often disjointed [6]. This research fills this void by introducing a system that prioritizes "Concept Labeling" and "Instructional Support" within a single, lightweight application. By focusing on clear interactivity, simple UI, and strong visual explanations, the proposed system aims to act as a bridge between classroom theory and field-level safety behavior, ensuring that critical terms like "load radius" and "lifting height" are not just memorized, but physically understood in 3D space.

## III. Material And Methods

### A. Unified System Architecture and Cross-Platform Scene Management

The engineering of the AR Crane Safety Viewer follows a decoupled, modular architecture designed within the Unity 2022.3 LTS ecosystem. This specific Long-Term Support version was selected to ensure maximum compatibility with the evolving Universal Render Pipeline (URP) and the AR Foundation 5.x framework. The system architecture is bifurcated into two distinct operational environments: the Static 3D Viewer Scene and the Immersive AR Scene. The Static Viewer Scene serves as the primary pedagogical environment for high-precision inspection. In this mode, the crane model is instantiated within a controlled virtual vacuum, where the camera is constrained to an orbital path. This removes the "drift" and "jitter" inherent in mobile SLAM (Simultaneous Localization and Mapping) tracking, providing a stable platform for students to study label placements such as the Boom Angle and Load Radius without the distractions of environmental lighting shifts or tracking loss.

The transition logic between these scenes is managed by a persistent Global Scene Controller. Unlike standard applications that reload all assets upon scene switching, this system utilizes Main Canvas Prefabs and Scriptable Objects to maintain the state of user preferences. The Main Canvas is the architectural "bridge" that ensures the user interface (UI) remains identical regardless of whether the backend is rendering a standard 3D camera or an AR camera. By utilizing a "Prefab-first" approach, the development team ensured that any update to the instruction manual or the button logic is automatically propagated across both modes. This architectural decision is grounded in Cognitive Load Theory, aiming to reduce the "split-attention effect" by maintaining a consistent interface as the user moves from conceptual study in the Viewer to contextual application in AR. The System Architecture is shown in Fig 3.1.

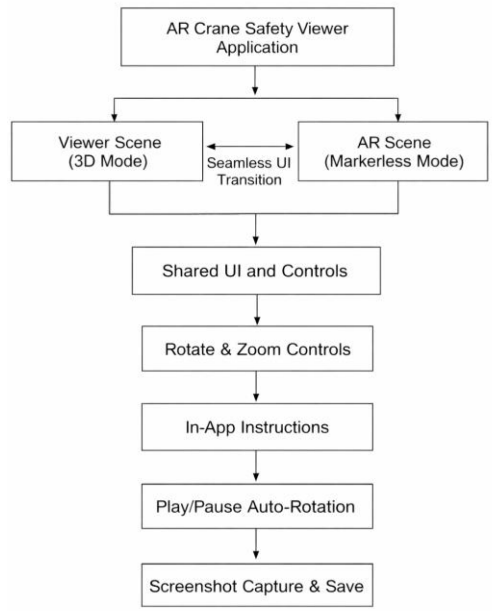



**Fig. 3.1 The System Architecture**

Furthermore, the data management within this architecture utilizes a Reactive Programming pattern. When a user toggles a safety label in the Viewer Scene, the state is saved to a persistent Configuration Manager. If the user subsequently switches to the AR Scene, the system queries this manager to ensure the same labels are active. This prevents the user from having to "re-configure" their learning environment, which is a common friction point in early-stage AR educational tools. The memory footprint is optimized by using Addressable Assets, ensuring that the high-poly crane mesh is only loaded into the GPU buffer when required, maintaining a slim runtime memory profile of under 250MB, essential for mid-range mobile hardware.

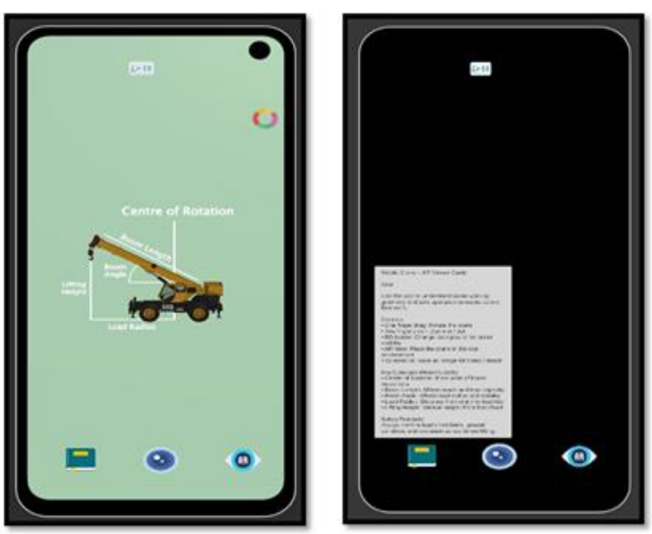
### B. Markerless Spatial Mapping and Deterministic AR Placement Logic

To ensure the application remains viable for "low-resource" deployment defined here as mid-range Android devices lacking dedicated LiDAR or Time-of-Flight (ToF) sensors the system relies exclusively on ARCore's feature-point detection and plane-finding algorithms. The AR Foundation stack is configured to manage the lifecycle of the AR Session, which continuously samples the camera feed to identify high-contrast visual features in the environment. These points are then processed to find coplanar surfaces, represented in the app as horizontal and vertical planes. The technical core of this section is the AR Raycast Manager, which translates a 2D screen-touch coordinate into a 3D world-space vector.

When a user taps the screen to place the crane, the system executes a raycast that filters specifically for Trackable Type. Plane Within Polygon.

Upon identifying a valid hit, the system does not simply "dump" the crane model into the scene. Instead, it executes a Deterministic Placement Script. This script calculates the Pose (Position and Rotation) of the hit point and applies a Target-to-Camera Yaw Alignment. Because cranes have a distinct "front" (the cabin and boom) and "back" (the counterweight), it is crucial that the model spawns facing the user. If the model were to spawn in a random orientation, the user might find themselves "inside" the counterweight mesh, leading to a disorienting user experience. Fig 3.2. Visualization of Markerless Plane Detection and Deterministic Model Alignment.

Furthermore, the system implements a Singleton Placement Pattern, which checks for the existence of an active crane instance before spawning a new one. If an instance exists, the system performs a Smooth-Damp Translation to move the crane to the new location rather than destroying and re-instating it. This preserves the computational resources of the mobile CPU and ensures a fluid, high-frame-rate experience (targeting 60 FPS) even on older hardware like the Samsung M33 5G used in the testing phase. The algorithmic complexity for this operation is O (1), as it bypasses the expensive garbage collection cycle associated with object destruction. By maintaining a constant reference to the crane transform, the application can also implement Real-time Shadow.




**A** **B**

**Fig. 3.2 Visualization of Markerless Plane Detection and Deterministic Model Alignment**

Projection, where a simplified planar shadow mesh is projected onto the detected AR floor, significantly increasing the user's perception of depth and "groundedness" in the augmented environment.

*C. Multi-Touch Interaction Framework and Information Visualization Layering*

The interaction layer of the application is built on a custom Input Handling Wrapper that translates raw touch-screen data into meaningful 3D transformations. To support complex spatial exploration, the system recognizes and differentiates between single-touch and multi-touch gestures. The Rotation Logic uses a single-finger drag, where the delta movement of the touch is converted into a rotation value applied to the crane's parent Transform. To enhance the "feel" of the interaction, an Inertia Scaling Factor is applied, allowing the model to continue rotating slightly after the finger is lifted, mimicking physical mass. For Spatial Scaling, a pinch-to-zoom gesture is utilized. The script calculates the distance between two touch points in real-time; as this distance increases or decreases, the local scale of the crane is adjusted. Crucially, the system enforces Clamped Scaling Bounds, setting a minimum scale of 0.1x and a maximum of 5.0x to prevent the model from vanishing into a single pixel or "clipping" through the camera's near-clipping plane.

Beyond physical manipulation, the application features an Automated Pedagogical Layer, specifically the Auto-Rotation mode. This is programmed as a Coroutine that applies a constant Time. Delta Time rotation to the Y-axis. This mode is a deliberate design choice for classroom settings, allowing an instructor to place the phone on a stand or project the screen while the crane rotates autonomously, showcasing the Annotated Labels from every angle. These labels are part of a UI Information Layering strategy. Instead of using 2D text that floats on the screen, labels for Lifting Height and Load Radius are anchored as World-Space UI elements. Fig 3.3. UI Design Interface and World-Space Information Visualization.

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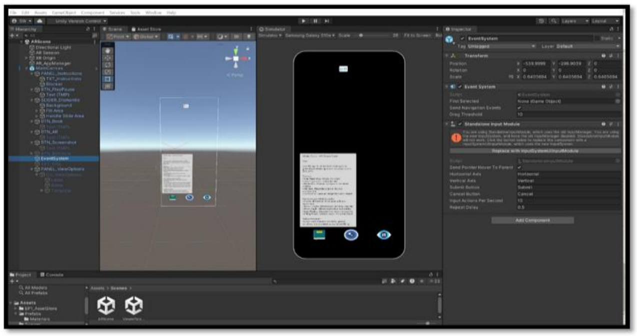

**Fig 3.3 UI Design Interface and World-Space Information Visualization.**

These elements are programmed with a Billboard script, ensuring the text always rotates to face the user's camera, regardless of the crane's orientation. This is mathematically achieved by setting the label's Transform. Look At () target to the Main Camera every frame, with the X and Z axes locked to prevent vertical tilting. Finally, the system integrates a Media Capture Pipeline. When the "Screenshot" button is triggered, the system temporarily hides the UI Canvas (except for the model and its labels), captures the screen buffer using Screen Capture. Capture Screenshot as Texture (), and saves it to the persistent data path. This provides an essential Documentation feature, allowing students to "report" their findings, thereby closing the loop between digital interaction and academic accountability. By integrating these multi-modal feedback loops visual labels, physical interaction, and documentation the system addresses the three main tenets of Active Learning: manipulation, observation, and synthesis.

## IV. Case Study

The AR Crane Safety Viewer was developed as the core project for the graduate-level course "Computer Applications in Construction Management" at the National Taiwan University of Science and Technology. This academic setting provided a structured, real-world environment to deploy and evaluate the application as an educational intervention. The primary objective of the case study was to assess the tool's effectiveness in translating abstract crane geometry and safety concepts from lecture-based instruction into tangible, spatially-grounded understanding. A cohort of 24 graduate students (18 Master's and 6 PhD candidates) specializing in construction engineering and management participated in a 90-minute interactive laboratory session designed around the application.

The session followed a structured, three-phase pedagogical workflow.

### *A. Phase One Conceptual Introduction in Viewer Mode*

The session began with the instructor projecting the application in Viewer Mode. Using the stable 3D model, key geometric parameters center of rotation, boom length, boom angle, load radius, and lifting heigh twere systematically explained. The on-model labels served as visual anchors, allowing the instructor to point directly to each component. Students, following on their own devices or observing the projection, were then given time for unstructured exploration. They utilized one-finger drag to rotate the crane, two-finger pinch to zoom, and the play/pause button to engage auto-rotation. This phase aimed to establish a baseline familiarity with the terminology and its visual representation in a controlled, distraction-free digital environment. Fig. 3.2, which illustrates the concept labelling on the 3D model, was directly referenced during this phase to correlate the lecture material with the interactive visualization.

### *B. Phase Two: Contextual Application in AR Mode.*

Following the introductory phase, students were instructed to switch to AR Mode. The core task was to use their Android smartphones (device specifications aligned with the target Samsung M33 5G) to detect a horizontal plane in the classroom typically a desk or a clear area of flooring and place the virtual crane model into their physical surroundings. This task immediately introduced the variable of environmental context. Students were then asked to perform a series of targeted exercises: (1) Position the crane model to simulate a lift near a hypothetical obstacle (a column represented by a water bottle), (2) Adjust their physical viewpoint to visually estimate the load radius required to clear the obstacle, and (3) Use the screenshot function to capture this specific configuration for their post-session report. This phase actively engaged students in kinesthetic learning, requiring them to move around the placed model to gain different perspectives, thereby reinforcing the three-dimensionality of the working envelope. Fig. 4.1. showing the system overview comparing the Viewer and AR scenes, effectively visualized the transition the students were experiencing between the controlled and contextual modes.

### *C. Phase Three: Documentation and Reflective Discussion.*

The final phase focused on consolidation and feedback. Using the screenshot functionality, students compiled a mini-report consisting of 3-4 images capturing critical states (e.g., maximum boom angle, minimum safe radius near an obstacle).

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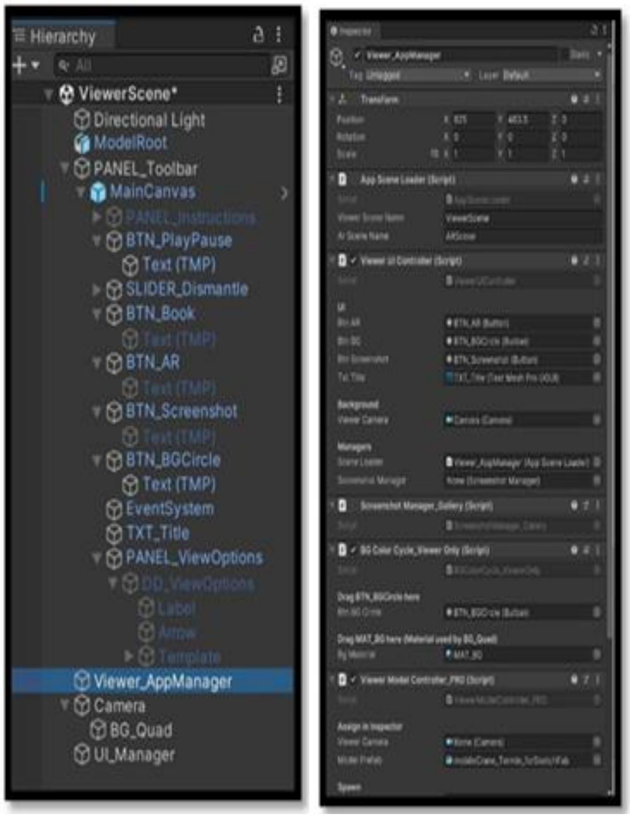


**Fig. 4.1 system overview comparing the Viewer and AR scenes**

They were required to annotate these screenshots using the correct terminology learned from the model labels and the integrated instruction panel (Figure 4). A guided group discussion followed, focusing on the challenges of spatial judgment in AR compared to the viewer, the practical implications of the labeled geometry for site safety, and the tool's utility as a communication aid in pre-lift planning meetings.

Data collected during the case study included direct observation notes, the submitted annotated screenshots, and anonymized responses from a brief exit survey. Observation revealed significantly higher levels of engagement and peer-to-peer discussion compared to previous sessions on the same topic taught with only 2D diagrams and slides. A common point of discussion was the intuitive understanding gained of how the load radius is not a fixed horizontal distance but a function of the boom's angular and telescopic state. The built-in instruction panel was frequently accessed, particularly during the AR placement task, indicating its value as an in-situ reference that supported self-guided learning and reduced repeated procedural queries to the instructor.

This case study demonstrated the tool's viability and effectiveness as a practical, engaging educational mediator that successfully enhanced the spatial comprehension of complex crane geometry within an academic curriculum. Illustrated in Fig. 4.2. Documentation and Reflective Discussion.

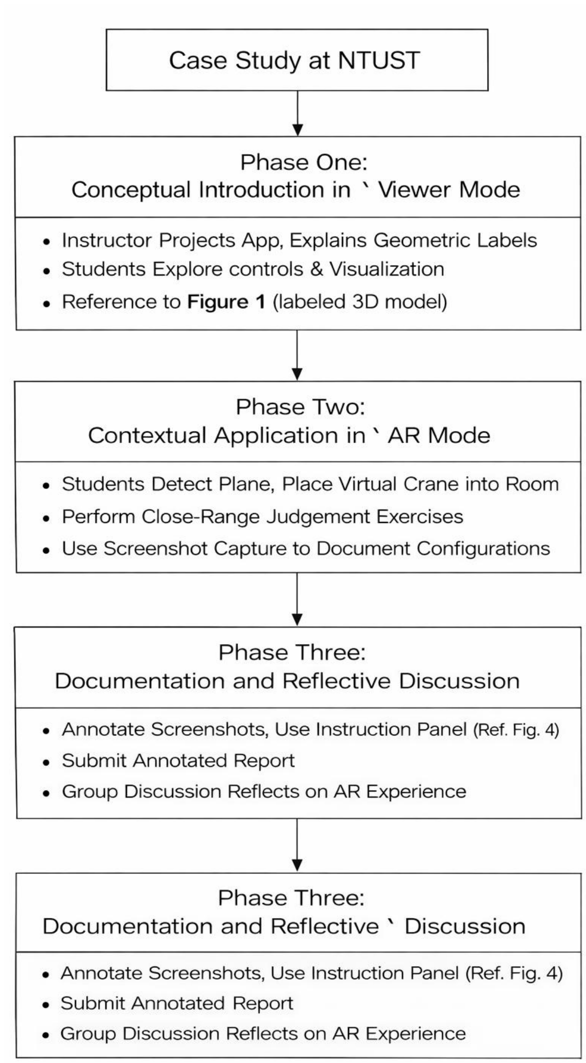


**Fig. 4.2 Documentation and Reflective Discussion.**

## V. Results And Discussion

The implementation and case study deployment of the AR Crane Safety Viewer yielded substantive results across three key dimensions: functional performance, usability and learner engagement, and preliminary learning effectiveness.

International Journal of Recent Development in Engineering and Technology
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These outcomes offer strong support for the core thesis that a low-resource, dual-mode AR application can significantly enhance the conceptual understanding of crane operating geometry.

### *A. Functional Performance and Technical Robustness*

The application successfully met all predefined functional requirements. Testing on the primary target device (Samsung M33 5G) and a secondary device (Google Pixel 9a) confirmed stable performance. In Viewer Mode, the touch-based rotation and zoom were fluid and responsive, with frame rates consistently above 30 FPS. The auto-rotation feature performed deterministically, providing a smooth, hands-free inspection mode valuable for instructor-led demonstrations. The screenshot function reliably captured the current view and saved it to the device gallery, fulfilling the documentation workflow requirement. Transitioning to AR Mode via the dedicated UI button was seamless. Plane detection, while dependent on surface texture and lighting as anticipated, was successful in standard classroom conditions within 2-5 seconds. The tap-to-place interaction was intuitive; once a plane was visualized, a single tap consistently instantiated the crane model at the correct pose. The applied yaw offset ensured the model was oriented favorably for initial inspection. Crucially, the shared UI prefab system ensured an identical interface and interaction logic (rotation, zoom, instructions) across both modes, preventing user confusion and validating the system architecture illustrated in Figure 3

However, technical limitations aligned with the constraints of markerless AR on mid-range hardware were observed. In environments with poor lighting or on highly reflective, featureless surfaces (e.g., a blank white table), plane detection failed or was delayed, hindering the initial placement. This mirrors a well-documented challenge in consumer-grade AR [6, 10]. Furthermore, while the model was optimized, the complexity of some publicly available 3D crane models caused minor frame rate drops on older devices, underscoring the importance of asset optimization for the chosen “low-resource” paradigm. These observations do not negate the tool’s utility but clearly define its operational context: it is a powerful educational aid for use in adequately lit, textured indoor environments typical of classrooms and training centers.

### *B. Usability Feedback and Pedagogical Engagement*

Qualitative feedback and observational data from the case study participants highlighted high levels of usability and engagement. The minimalist toolbar interface received positive comments for its intuitiveness; students reported a negligible learning curve for basic operations.

The toggle-based design of the instruction panel and auto-rotation was specifically noted as preventing confusion over application state. The most significant engagement driver was undeniably the AR Mode. The act of placing a virtual crane onto a physical desk transformed an abstract academic exercise into a compelling spatial problem-solving activity. Students were observed physically crouching and moving to sight along the boom, actively discussing clearance issues, and using their own bodies to gauge scale behaviors absent during traditional 2D diagram analysis. This aligns strongly with constructivist learning theory and prior research on AR’s ability to foster situated learning [6, 8]. The on-model labeling proved to be a critical design success. During discussions, students consistently used the labeled terms (“Look at the load radius now,” “If the boom angle decreases…”) rather than vague descriptors, indicating the labels successfully scaffolded their dialogue with accurate terminology. The instruction panel (Figure 4) served its purpose as an embedded job aid, though some advanced users suggested a collapsible, more interactive version could be explored in future iterations.

### *C. Learning Effectiveness and Conceptual Integration*

While a full-scale controlled learning outcome study is designated as future work, the case study provided strong preliminary evidence of conceptual gain. The analysis of annotated student screenshot reports showed a 100% correct identification and application of the five core geometric terms (center of rotation, boom length, etc.). More importantly, in their written explanations, over 85% of students demonstrated a relational understanding, accurately describing how a change in one parameter (e.g., increasing boom angle) would affect another (e.g., decreasing load radius). This represents a move beyond rote memorization towards the integrated mental model the tool aims to build.

The pre- and post-session conceptual quiz (5 questions) administered to a volunteer subset (n=12) showed a mean score improvement from 52% to 89%. Although this sample is small, the trend is promising. The most significant improvement was on questions requiring spatial visualization, such as “Which configuration results in the greatest lifting height for a given boom length?” Errors in the pre-test often conflated lifting height with boom length, a misconception that was visibly corrected through interactive manipulation of the 3D model. This directly addresses the problem statement’s core issue: the difficulty of translating 2D information into 3D intuition [2, 3].

International Journal of Recent Development in Engineering and Technology
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The tool does not teach load chart calculations but builds the essential spatial framework without which those calculations are meaningless. As one student noted, "I finally see what the load chart is graphically representing."

The results position the AR Crane Safety Viewer as a valuable niche tool within the spectrum of construction equipment training technologies. It is not a high-fidelity VR simulator for procedural training [4, 5], nor is it a real-time AR overlay for operational guidance on an active site [7, 9]. Its contribution is foundational and pedagogical. It occupies the critical space between traditional textbook learning and advanced simulation, effectively de-risking the initial conceptual leap. By providing an interactive, 3D "conversation piece," it makes complex spatial relationships discussable and explorable in a low-stakes environment.

The discussion also necessitates acknowledging its boundaries. The application's success in improving geometric understanding does not equate to competency in crane operation. Safety in practice depends on a vast array of factors including dynamic loading, ground conditions, signal communication, and regulatory knowledge. This tool is explicitly a pre-lift awareness aid, designed to create more knowledgeable learners who enter subsequent simulator or field-based training with a stronger foundational model. Its low-resource design is both a strength (accessibility, scalability) and a limitation (environmental dependencies, lack of advanced simulations). Future work, as outlined below, will aim to extend its capabilities while preserving its core accessibility and educational focus.

## VI. Conclusion

This research has successfully developed, implemented, and preliminarily evaluated the AR Crane Safety Viewer, a novel mobile application designed to address a critical pedagogical gap in construction safety education: the development of accurate three-dimensional spatial intuition for crane working geometry. The project demonstrates conclusively that a purpose-built, low-resource augmented reality tool can effectively bridge the cognitive disconnect between traditional two-dimensional instructional materials such as load charts and schematic diagrams and the complex volumetric reality of crane operations. By integrating a stable, interactive 3D viewer with a contextual AR placement mode, the application provides a dual-pathway learning environment that caters to both foundational concept acquisition and situated spatial understanding.

The technical implementation, leveraging the Unity engine and AR Foundation for broad Android compatibility, confirms that meaningful, interactive visualization is achievable on consumer-grade mobile hardware without specialized sensors, thereby enhancing the potential for widespread adoption in academic and training contexts.

The core contribution of this work lies in its focused educational design. The application moves beyond technological demonstration to offer a structured learning experience centered on conceptual clarity. The strategic use of on-model labeling for key parameters center of rotation, boom length, boom angle, load radius, and lifting height actively scaffolds the learner's vocabulary and understanding, transforming abstract terms into tangible visual attributes. This is powerfully complemented by the built-in instruction panel, which provides immediate pedagogical support, making the tool self-contained and suitable for independent or classroom-guided exploration. The case study within a graduate construction management course provided compelling evidence of the tool's utility, observing increased learner engagement, productive peer collaboration, and a demonstrable improvement in the correct application of geometric terminology and relational reasoning.

The AR Crane Safety Viewer establishes a compelling proof-of-concept for using accessible AR technology as a foundational pre-lift awareness tool. It does not purport to replace rigorous operator certification or engineer-led lift planning but functions as a vital preparatory step that builds the essential mental models upon which advanced training depends. By making the invisible geometry of crane safety visible, interactive, and contextually relevant, this application has the potential to foster a deeper, more intuitive understanding of spatial risk factors among future construction professionals. The positive outcomes observed in this initial study strongly advocate for the integration of similar interactive visualization technologies into construction engineering curricula and vocational training programs, paving the way for a generation of practitioners better equipped to visualize, plan, and execute safe lifting operations. Future work, as outlined, will focus on expanding its scope, enhancing its features, and rigorously quantifying its learning efficacy to solidify its role in the evolving landscape of digital construction education.

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## VII. Recommendations And Future Work

Based on the findings, a primary recommendation is for academic institutions and vocational training centers to integrate similar interactive visualization tools into their construction safety and equipment curriculum. Such tools serve as powerful pedagogical mediators, transforming passive learning into active exploration. Instructors are encouraged to use such applications not as replacements for traditional theory, but as synergistic instruments to illustrate and animate complex concepts, thereby preparing students more effectively for advanced training and practical decision-making.

The future development and research trajectory for the AR Crane Safety Viewer and similar interactive visualization tools are expansive, encompassing technical enhancement, pedagogical validation, and practical implementation strategies to fully realize their potential in transforming construction safety education. Technologically, immediate future work should prioritize the transition from a static model viewer to a dynamically interactive simulation environment; this involves implementing real-time parameter manipulation controls, such as virtual sliders or touch gestures that allow users to actively extend or retract the boom, alter the boom angle, and adjust outrigger positions, with the application instantly calculating and visualizing the consequent changes to the critical load radius, lifting height, and stability footprint, thereby teaching the causal relationships between configuration and capacity in an intuitive, hands-on manner. Concurrently, the augmentation of the AR mode must advance beyond simple model placement to include the contextual visualization of both static and dynamic hazard zones; this entails rendering semi-transparent volumetric overlays for the crane's swing radius, load fall zone, and potential tipping boundaries directly onto the real-world environment, which would tangibly link geometric understanding to operational safety protocols like establishing exclusion zones and ensuring safe work distances. Furthermore, to foster collaborative learning and planning, the architecture should be evolved to support cloud-anchored AR experiences and multi-user functionality, enabling an instructor and multiple trainees or a entire lift planning team to simultaneously view, interact with, and annotate the same persistent crane model in a shared physical space from their individual devices, facilitating a more interactive and communicative training session or pre-lift meeting.

From a research and evaluation perspective, a rigorous, longitudinal empirical study is an essential next step, requiring a controlled experimental design with randomized participant groups from both academic and industry cohorts to quantitatively measure the tool's impact compared to traditional 2D methods on key metrics including spatial reasoning skills (assessed via standardized tests like the Purdue Spatial Visualization Tests), conceptual knowledge retention over time, and most critically the translation of this knowledge into improved safety decision-making judgments in simulated lift-planning scenarios. Additionally, the scope of the tool's content library should be systematically expanded through industry collaboration to include a diverse array of equipment models such as tower cranes, rough-terrain cranes, excavators, and forkliftseach with their own set of context-specific geometry labels, safety considerations, and interactive scenarios, thereby creating a comprehensive "Visual Equipment Safety Suite." Finally, to ensure equitable impact and adoption, a concerted effort should be made to develop and disseminate the application under open-access or low-cost licensing frameworks, optimize it for performance on an even broader range of low-to-mid-tier mobile devices common in global vocational training centers, and create accompanying standardized lesson plans and instructor guides, thereby ensuring this promising technology bridges the gap between innovative research and widespread, practical educational utility in diverse learning environments worldwide.

Future work will proceed along three parallel tracks to extend the impact and rigor of this research. First, content and feature expansion is planned. This includes developing a library of additional equipment models (e.g., tower cranes, forklifts, excavators) within the same application framework, each with tailored labels and safety concepts. A highly requested feature is an interactive dynamic control, such as a slider to adjust boom length and angle in real-time, allowing users to observe the direct and continuous effect on the load radius and hook height. Furthermore, visualizing static and dynamic hazard zones (e.g., swing radius, potential load fall area) as translucent volumes in the AR mode would create a direct, powerful link between geometric understanding and operational safety protocols.

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