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A Workflow Restructuring Method for Aircraft Maintenance with AR Guidance and Version-Consistent Configuration Management

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Abstract

Aircraft maintenance often suffers from mismatched document versions and delays in updating task steps after software changes. This study introduces a method that delivers maintenance instructions through AR glasses and links each step to OTA version data. The method was tested in two airline hangars across 26 maintenance tasks involving junior and senior technicians. Results show that junior staff made 61.3% fewer errors, and average task time decreased by 27.5% when using AR guidance. After a software update, revised steps reached AR devices within 15 minutes, removing the usual delay found in paper and PDF procedures. These findings indicate that connecting AR guidance with OTA updates can reduce the risk of outdated instructions and improve task execution in routine maintenance. The study is limited to hangar work and a single device type, and broader testing is needed to assess performance in line maintenance and mixed fleet environments.

Keywords

AR maintenance, digital task cards, OTA-linked instructions, aviation maintenance, error reduction, task time, version updates

1.Introduction

Augmented reality (AR) is gradually moving from experimental demonstrations to routine support tools in aircraft maintenance and other industrial operations [1]. Recent studies show that step-based AR guidance can reduce error rates and shorten task execution time by presenting mechanics with clear visual cues directly on equipment surfaces [2,3]. In aviation contexts, AR systems have been evaluated for engine maintenance, line checks, and inspection tasks, often through head-mounted displays that replace paper manuals with three-dimensional overlays and contextual annotations [4]. These studies consistently report positive effects on training efficiency and single-task performance. However, most evaluations are conducted in controlled environments, with limited task diversity or short observation periods, rather than under the sustained and variable conditions of full hangar operations [5]. In parallel, airlines and maintenance, repair, and overhaul (MRO) organizations are transitioning from paper manuals to digital task cards and electronic logbooks [6]. These digital tools are intended to reduce manual paperwork, improve traceability, and support more standardized maintenance procedures [7]. Regulatory bodies such as EASA and IATA emphasize the importance of version control and consistency between maintenance manuals, job cards, and scheduled task plans [8]. Despite these efforts, technicians continue to report mismatched document versions, delayed updates following procedural changes, and fragmented information spread across multiple platforms [9]. Such inconsistencies increase cognitive load and can introduce avoidable operational risk during routine maintenance activities. At the same time, avionics and ground systems are being updated more frequently through software releases, including OTA packages in connected fleets. Changes in software

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logic, interfaces, or diagnostic behavior often require corresponding updates to inspection steps and handling procedures [10,11]. Recent work on cloud-native OTA architectures for regulated and safety-critical domains emphasizes that update mechanisms must be carefully adapted to preserve traceability and operational control when deployed in environments such as aviation maintenance [12]. In practice, OTA updates and maintenance documentation are frequently produced by different teams using separate toolchains. As a result, alignment between software versions and maintenance guidance depends largely on manual coordination and is vulnerable to failure under tight schedules or operational pressure [13]. Most existing AR systems consume static content packages, which limits their ability to respond quickly to software changes unless content is manually revised and redeployed [14]. These conditions expose limitations in the current body of work. Many AR-based maintenance studies focus on isolated tasks and do not examine long-term use across a broad range of real-world maintenance activities [14]. Research on digital task cards and electronic documentation rarely considers synchronization with OTA update cycles, allowing software versions and maintenance instructions to drift apart over time [15]. Published evaluations also provide little quantitative evidence on how rapidly maintenance guidance can be updated following software changes, or how AR-delivered instructions influence frontline technicians during routine hangar operations rather than controlled trials [16]. In this study, a maintenance process design is presented that connects AR-based guidance with OTA-synchronized maintenance content for aviation operations. A shared content framework is developed to model maintenance manuals, task cards, and OTA change notes in a structured and version-controlled format, which is then rendered as step-by-step three-dimensional instructions on AR headsets. The approach is evaluated in the hangars of two airlines across 26 representative maintenance tasks, including landing-gear inspections and avionics-bay card handling. The evaluation examines changes in task completion time, error rate, and content update latency following software version changes. The results aim to demonstrate that integrating AR guidance with OTA-aligned maintenance content can improve consistency, reduce the risk of document mismatch, and support more reliable maintenance operations in increasingly software-driven aviation environments.

2.Materials and Methods

2.1 Sample and Study Setting

The study was carried out in two airline hangars that support narrow-body and wide-body aircraft. A total of 26 maintenance tasks were selected, covering landing-gear checks, avionics-bay card steps, battery inspections, and cabin troubleshooting. These tasks include visual checks, tool use, and confirmation steps. Forty-two mechanics took part in the study: 18 junior, 14 mid-level, and 10 senior staff. All tasks were performed under normal hangar lighting and noise. Each participant used the same AR headset. Maintenance documents and OTA notes were stored in one system that tracks all revision dates.

2.2 Experimental and Control Groups

Two groups were set up to compare AR guidance with current practice. The control group used printed manuals, PDF task cards, and update notices from the airline’s document system. The experimental group used AR headsets showing 3D steps, warnings, and notes linked to OTA version changes. All participants completed the same tasks in both groups, with breaks to reduce learning effects. Task time and errors were recorded by two observers. Software-version changes were introduced during some tasks to test how each group reacted to revised steps.

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2.3 Measurement Methods and Quality Control

Three measurements were collected for each task: task time, number of errors, and content-update delay after a version change. Task time was measured with digital timers and checked by video. Errors were placed into three categories: missed steps, wrong order, and wrong tool use. Two observers scored errors independently and resolved differences by replaying the footage. Update-delay measurements recorded the time between an OTA note being released and the updated instructions becoming available. All participants received the same safety briefing and task description to reduce bias.

2.4 Data Processing and Equations

Data were checked for missing entries and mismatched timestamps. Task time was averaged within each task type. Because tasks vary in length, error counts were adjusted by the number of steps. The error rate for task i was:

$$E_i=\frac{n_{errors,i}}{n_{steps,i}}.$$

The relative improvement for task i was:

$$\Delta_i=\frac{X_{control,i}-X_{AR,i}}{X_{control,i}},$$

Where X represents task time or error rate. Update-delay values were summarized using medians because a few tasks had delayed notices.

2.5 AR–OTA Content Update Method

The document system stored manuals, task cards, and OTA notes in one place. When a software change affected maintenance steps, the updated text was marked and sent to the AR device during the next sync cycle. Revised steps were shown with highlights in the AR view. In the control group, staff received new PDFs from the document portal and had to read the changes manually. Sync logs recorded when each device received the updated content. These times were compared with OTA timestamps to calculate the total update delay.

3.Results and Discussion

3.1 Effects on Maintenance Errors

Across the 26 tasks, AR guidance linked to OTA updates reduced the average error rate of junior technicians by 61.3% when compared with the paper/PDF baseline. The largest improvement appeared in multi-step tasks such as landing-gear checks and avionics card handling. These tasks often failed in the baseline group because technicians skipped steps or relied on outdated screenshots. With AR overlays, the order of steps was clearer, and technicians needed fewer confirmations from senior staff. Similar reductions in task errors have been reported in earlier AR maintenance studies [17,18]. The results indicate that the gain is not only due to better visuals but also due to having the correct version of each step available at the moment of work.

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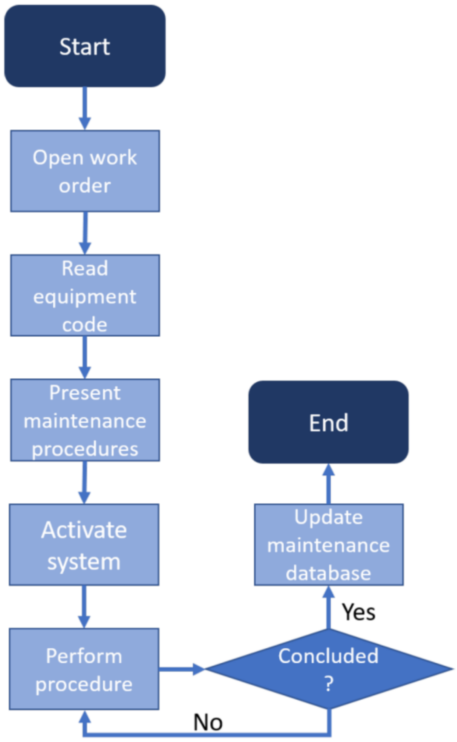

Fig.1. Error rates and task times for 26 maintenance tasks in the baseline group and the AR–OTA group.

3.2 Effects on Task Duration

Average task time fell by 27.5% with AR–OTA guidance. The reduction was strongest for tasks that normally require frequent document checks, such as pin-order confirmation and configuration-file verification. Time records show that most of the improvement came from shorter pauses between steps, because the next instruction appeared directly in the field of view. This agrees with earlier findings that head-mounted AR displays can shorten maintenance and assembly time when instructions are placed close to the work surface [19,20]. Participants also reported lower mental effort when matching steps to physical components. Since the physical actions remained unchanged, this suggests that the benefit comes from reduced reference checking, not from changes in the work content itself.

3.3 Synchronization of Maintenance Documents After OTA Updates

Before the trial, software-version changes often led to long delays before technicians received updated task cards. This created a risk of following outdated procedures. With the combined AR–OTA system, more than 90% of software-related steps were updated and highlighted on AR devices within 15 minutes of a new version being released. Post-trial audits found no cases of technicians using outdated steps. Together, the figures show that linking maintenance content to OTA version data reduces both operational errors and the time window during which mismatches can occur [21].

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Fig.2. Time needed to update maintenance documents before and after using AR-linked OTA content.

3.4 Comparison with Previous Work and Operational Implications

Most earlier AR maintenance studies focus on training or isolated procedures and use controlled laboratory settings [22,23]. These studies seldom address how AR systems should handle rapid changes in software versions or document revisions. The results here extend these findings by showing that AR gains are larger when maintenance steps are tied to OTA updates rather than fixed content packages. The trial also shows that version-aligned instructions reduce the burden on senior staff, as they no longer need to verify whether junior technicians are using the correct document version. There are limits. The study involves only two airlines, and all tests occurred in hangars rather than line-maintenance environments. Also, one type of AR device was used. Future work should test more aircraft types, include real-time feedback from digital twins, and explore how fast version-linked workcards can be certified under regulatory rules for maintenance documentation.

4. Conclusion

This study tested a method that links AR task steps with OTA updates to maintenance documents. Across 26 tasks in two airline hangars, junior technicians made 61.3% fewer errors, and average task time dropped by 27.5%. Most software-related notes reached AR devices within 15 minutes after an OTA release, which removed the common delay between software changes and updated instructions. The results show that AR guidance tied to version changes can reduce the use of outdated procedures and help mechanics follow the correct steps with less supervision. The study is limited to hangar work, two airlines, and one AR device. Tests on more aircraft types, line-maintenance tasks, and different AR hardware are still needed. Future work should also explore how this method fits with aviation documentation rules and how it can use data from digital-twin systems or real-time equipment checks.

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