Augmented Reality Authoring for Efficient Inspections in Green Aviation: Evaluating Accuracy and Usability

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Abstract. This paper addresses the gap in AR-guided inspection by developing and evaluating an AR authoring tool tailored for green aviation. The tool aims to overcome the current limitations by assisting the inspector in the data acquisition process using hand-held sensors. The study introduces a sensor guidance prototype applicable to various inspection scenarios prone to human error. Usability assessments reveal positive feedback on real-time guidance and an intuitive interface, though challenges in tracking accuracy and managing complex trajectories are identified, particularly with the Microsoft HoloLens 2. Testing on the Magic Leap 2 (ML2) showed sufficient position accuracy of 1.39 mm, suitable for mobile authoring and tracking of trajectories. While results are promising, further optimization in tracking, user interface (UI), and real-world validation is needed.

Keywords: Augmented Reality Authoring · Augmented Reality for Inspection · Sensor Trajectory Guidance · AR Accuracy Analysis · Inspection Assistance

1 Introduction

In recent years, Augmented Reality (AR) has gained attention due to its potential to optimize manual industrial processes. Its application in maintenance, repair, and overhaul operations (MRO) remains relatively unexplored [1]. MRO relies on hand-guided sensors for inspections, where manual operation and sensor-specific guidance requirements (e.g., maximum velocity) directly impact data quality. Unlike assembly, where the final product offers a clear indicator of process quality, evaluating the manual data acquisition process is challenging. This is particularly crucial in aviation, where large-scale structures and the emergence of new, hydrogen-based propulsion technologies need reliable, mobile inspection solutions (e.g., leakage inspection) [2]. AR offers a promising solution

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by providing real-time information on sensor guidance and sensor trajectory supervision, enhancing both the accuracy of inspections and, ultimately, passenger safety [3].

Though widely explored for assembly tasks, research on the application of AR in inspection remains limited [1]. Existing research demonstrates the effectiveness of AR in mobile inspection applications, using information overlay for improvements in inspection efficiency [4]. [5] introduces a successful AR application for operator training evaluating performance metrics from process execution but only focusing on assembly tasks. Similarly, [6] aims to provide operators with real-time information about tasks in a manufacturing environment and trajectories of mobile robots but suffers from limitations in tracking accuracy and comprehensive evaluation of real-time AR data. Despite these limitations, both [6] and [5] show promising research directions in providing feedback mechanisms, 3D model overlay, and intuitive interfaces to minimize cognitive load, indicating promising applications for enhancing the quality of manual sensor guidance. Robust and precise tracking remains a significant challenge in AR-guided inspections, directly impacting the accuracy of guidance [4]. A research gap exists in applying these tracking methods for sensor guidance applications compatible with various hand-guided sensors. [5] identifies the preparation time of AR applications as a significant drawback, while [6] emphasizes the importance of streamlining authoring processes to reduce deployment time and effort for wider adoption. [6] further demonstrates the positive impact of using AR also for authoring purposes on user experience, reduced time and errors. Advancements in AR robot programming [7] significantly improve speed and user confidence. Although AR shows excellent promise for tracking and authoring in sensor guidance applications, no known publications have specifically addressed this issue.

This research addresses the gap in AR-guided inspection by investigating a novel application for authoring inspection procedures, specifically within green aviation. This study will develop and evaluate an AR sensor guidance demonstrator applicable to multiple inspection use cases. Key design decisions will be outlined, and the usability of the proposed solution will be assessed through a user study. Crucially, a detailed accuracy analysis of tool tracking will be conducted, evaluating the technological foundation of the authoring solution and providing valuable insights for future research in AR-guided inspection.

This work is structured as follows: we examine two user roles and specific use cases to derive generalizations, compare their challenges, provide an overview of requirements for AR authoring, as well as methods (Sect. 2), for a prototype implementation of our modular authoring tool (Sect. 3). Main aspects such as usability and achievable accuracy are investigated (Sect. 4). Finally, we summarize our findings, discuss limitations, and identify areas for improvement (Sect. 5).

2 Approach and Methodologies

This section defines the main user roles, two relevant aircraft inspection use cases, and key requirements for the AR application and hardware. Methodologies for authoring and the conducted user study and accuracy analysis are presented.

The **User Role** *"Author"*, also referred to as the process expert, is primarily responsible for the adaption to specific environments and defining the parameters for inspection procedures, including the optimal trajectories, tolerance zones, speeds, and angles (Fig. 1[2]). The authoring tool is configured with the help of the author's knowledge and experience in the field, which includes path optimization and testing in accordance with sensor requirements and best practices, as well as preparing localization (e.g., position markers...). The user role *"Inspector"* utilizes the application generated by the author to carry out the inspection, missing the level of expertise or experience as the author. They follow the guidelines and procedures embedded in the application to ensure the inspection is performed accurately and efficiently (Fig. 1[1]). The inspector application visualizes sensor-specific trajectories for operators, providing live feedback on the current sensor pose, velocity, and acceleration. After starting the application, they have to maintain alignment with the defined trajectory inside a tolerance zone, performing manual adjustments to the sensor position.

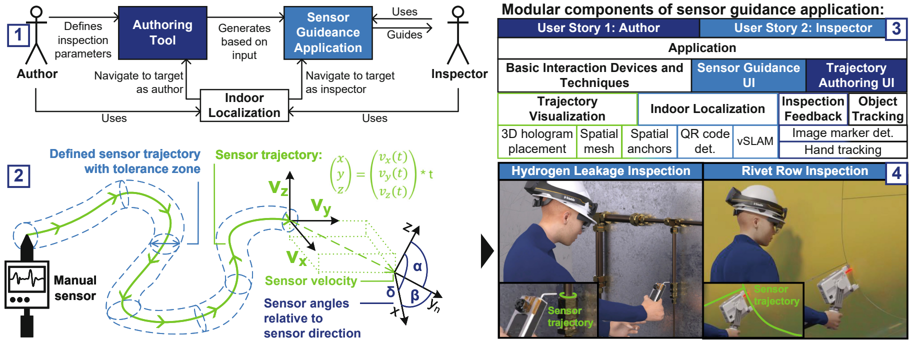


Fig. 1. Visualization of user roles flow chart [1], sensor trajectory [2], modular application components [3] and inspection use cases [4]

Two relevant **Inspection Use Cases** in aviation represent variability in manual sensor trajectories specific to sensor characteristics and emphasize the requirements of the proposed AR authoring solution (Fig. 1[4]):

Hydrogen Leakage Inspection: Aircraft with hydrogen-based propulsion systems require regular checks for leaks due to hydrogen's volatility and flammability. A hydrogen sniffer is used, requiring precise movement over potential leak surfaces. The sensor must maintain a specific distance and speed due to hydrogen's rapid dissipation. Challenges include homogeneity of measuring environment, gas invisibility, and sensor signal delay, all of which can be mitigated by AR support.

Aircraft Rivet Row Inspection: To ensure aircraft fuselage safety, rivet row inspections measure rivet placement and spacing for load distribution. Critical parameters include rivet pitch, edge distance, and height. A laser line scanner and encoder generate a point cloud, analyzed by software. Accurate data recording depends on maintaining specific angles, distances, and speeds, visualized through an AR application. Table 1 compares the specific sensor parameters for both inspection scenarios, highlighting key differences. While both scenarios require adherence to speed limitations, only rivet row inspection necessitates specific angle observations due to the nature of the laser scanning process.

Table 1. Definition of sensor trajectories for the seleted use cases

Trajectory Requirements		
use case	Leakage Inspektion	Riviet Row Inspection
Velocity	max. 10 mm/s	max. 20 mm/s
Trajectory Tolerances	3 mm	10 mm
Angle Tolerance	–	$\boldsymbol{\Delta}\alpha$, $\boldsymbol{\Delta}\beta$, $\boldsymbol{\Delta}\delta = \pm 10°$
Inspection Duration	10 s for fitting; 1 m pipe 10 s	1 rivet 2 s
Shape of Trajectory	Cylindrical (pipe), Torus (fitting sealing)	Cylindrical above riviet row

We will now outline the **General Requirements** for an AR application design to support manual sensor guidance after fostering understanding using inspection examples. An effective authoring process should incorporate trajectory definitions that are adaptable to various inspection scenarios, utilizing standardized trajectories in three-dimensional Euclidean space. Authoring involves modular software adaptable to different scenarios and integrated with the application's functionalities. The user feedback and mechanisms for interaction must be non-intrusive, clear, and easily understandable to avoid disrupting the inspection process [8]. Precise and easy setup of hologram placement employing tracking is critical for authoring to facilitate trajectory use. Visual feedback indicating sensor positions or user interactions is vital due to workplace conditions and the need for language-free communication.

Following the presentation of the requirements, the methodological essentials are presented, which include choosing authoring methods, selecting hardware, and methods for user study and analyzing accuracy.

The **Method for Sensor Trajectory Definition** is a key aspect of designing the required authoring solution. A defined target trajectory consists of ordered points in space, describing motion, velocities, and accelerations while incorporating sensor- and task-specific tolerances (Fig. 1[2]). Based on robot programming methodologies, two primary categories for defining sensor trajectories are identified: Offline and Online Programming.

Offline programming leverages CAD software and model-based approaches to generate trajectories without requiring access to the physical object. Combined with formalized sensor-specific knowledge [5], this method presents a high potential for automation [9]. However, further research is necessary to evaluate its effectiveness, particularly regarding the usability of authoring tools and the impact of model accuracy on the resulting trajectory.

In contrast, *online programming* generates trajectories directly on the physical object, utilizing tracking methods to compensate for real-world tolerances, thus eliminating the reliance on precise 3D models. Integrating online programming within an AR application allows intuitive user interaction and definition of trajectories through hand-guided programming [7], addressing navigation and UI inefficiencies of 2D interfaces [5].

AR online authoring thereby enhances effectiveness and user experience by allowing direct trajectory modifications, flexibility and immediate testing within the AR environment. AR technology enables mobile tracking, crucial for inspecting large structures like aircraft. Using the same tracking hardware for authoring and inspection reduces setup effort. While offline authoring offers automation, the infrequent need for new trajectory authoring in aircraft inspection prioritizes quick sensor and inspection process utilization. Therefore, we adopt online AR authoring for its ease of use, adaptability, and missing precise models in various industries.

The chosen **Hardware Technology** are AR head-mounted displays (HMD) for hands-free functionality and flexibility. Despite alternatives like ML2 and Vuzix Blade offering features like higher tracking accuracy and lighter weight, the HL2 was selected for its strong community support and extensive software compatibility[5], making it the most suitable option for developing our application.

The initial **User Study** was focused on usability, expecting feedback for a follow-up study. Authoring efficiency and accuracy analyses were not conducted at this stage. The User Study employed the System Usability Scale to validate the developed prototype on the HL2, assessing its usability and limitations in a simulated inspection scenario (Fig. 2). A SUS questionnaire, combined with custom and open-ended questions, gathered detailed feedback on the tool's use case suitability and areas for improvement. The study, performed on real aircraft components, involved participants (10 male, two female) executing key functionalities, including localization setup and a combined author/inspector workflow.

A separate **AR Tracking Accuracy Analysis** was conducted using the ML2. The user study identified limitations in the tool tracking of the HL2 requiring millimeter-level precision. ML2 offers enhanced capabilities for tool tracking, including a handheld controller with independent SLAM-based tracking. To evaluate the ML2's accuracy, the AR HMD was placed in four static positions (P1-P4 HMD) (Fig. 3), while the controller, mounted to a UR10e robot for precise movement, was tracked at seven defined points (Fig. 3). The AR pose data was compared to a commercial tracking system for accuracy assessment. Metal pipes were used as a background to create a realistic environment.

3 Implementation

We selected the HL2 for our implementation leveraging its capabilities, using the Mixed Reality Toolkit (MRTK) for most functionalities, ensuring seamless integration and support. Our application combines marker-based and markerless tracking to enhance accuracy and robustness (Fig. 1[3]). Vuforia was chosen for image marker detection because it offers superior performance in terms of accuracy and reliability, outperforming other options like ArUco markers, which are not supported anymore by HL2. The tool is designed to be intuitive for non-programmers, although specific environment adaptation requires training.

Authors set inspection parameters and environmental settings through a JSON file, using pre-measured inspection areas and strategically placed QR codes for localization, including marker IDs and previously defined trajectories. If no QR code is detected after starting the application, the system relies on vSLAM to update the user's position and orientation, ensuring consistent tracking. All user role functions, such as a live map, are selectable via a menu (Fig. 2[1]). Spatial Anchors, supported by MRTK, allow users to create trajectories by placing anchors on a spatial mesh. These anchors are linked to form a visual inspection path, with numerical labels guiding the user through the sequence (Fig. 2[2]). Trajectories are created via a pitch gesture or a tracked tool supported by raycasting. The author, as well as an inspector, can choose between tool or hand tracking, while hand tracking has a better performance. The designed tool features a cube on top, with each face holding Vuforia markers to ensure precise TCP determination.

This design supports real-time visualization of metrics such as speed, distance to trajectory, and angle, providing inspectors with immediate, actionable feedback (Fig. 2[3]). By integrating MRTK's Spatial Anchors, Vuforia for marker detection, and vSLAM for indoor localization, the application balances the precision of marker-based tracking with the adaptability of markerless methods, offering a robust solution tailored to industrial inspection tasks lag (Fig. 1[1][3]).

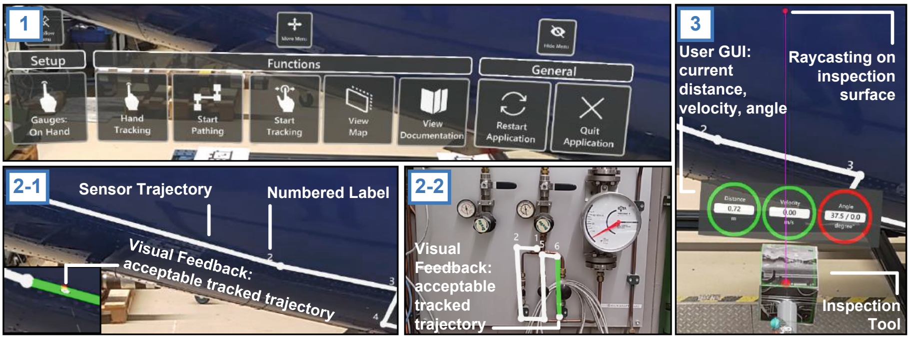
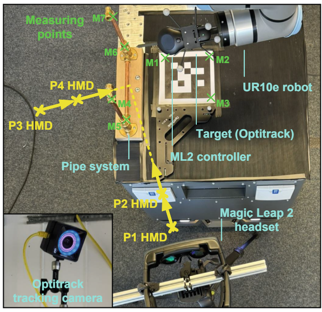


Fig. 2. Visualization of the developed AR user interface

4 Results

The **User Study** provides an average SUS score of 76 ($\sigma = 13{,}46$) for the standard questionnaire and 73.125 ($\sigma = 18{,}47$) for the custom one, both above the benchmark score of 70, indicating above-average usability but below the 80 threshold for excellent usability [10]. While the tool is deemed usable, feedback suggests areas for improvement. Issues include accuracy and efficiency performance due to lagging tool tracking features using Vuforia. Additionally, the menu UI requires a clearer feature presentation. Most participants feel the AR authoring tool performs better for rivet row inspection on aircraft fuselages, as the spatial mesh of the fuselage is more accurate than that of pipes. They note that the tool references the wall behind the pipes rather than the pipes themselves. Additionally, the tool's missing support for various trajectory types, such as curved or circular, makes inspecting pipe connectors for hydrogen leakage detection challenging. The results of the study suggest a further investigation of tracking accuracy.

We **Evaluate the AR Tracking Accuracy Using ML2**, based on the user-study findings. The ML2 is an alternative AR Hardware that promises improved performance with its additional controller for tool tracking. Our primary objective was to determine whether ML2's enhanced quantified tracking capabilities address the deficiencies observed with the HL2. Results show a maximum position repeatability of 0.0475 mm (Ø 0,2621 mm) and position accuracy of 1.39 mm (Ø 1,6172 mm), satisfying both use case requirements. Positioning the HMD at optimal angles and reduced distances from the pipes up to 300 mm affected position repeatability and accuracy (Fig. 3). Accuracies were higher after the initial measurement at the first HMD position due to SLAM tracking adjustments, as no calibration was carried out to reduce setup effort.



Analyses were carried out in accordance with EN ISO 9238

Measurement series	HMD distance [mm]	AR Position Repeatability [mm]			AR Position Accuracy [mm]		
		mean	max	min	mean	max	min
0 (initial)	700 mm (P1)	0,4136	6,3847	0,1063	1,6669	5,8435	0,4704
1	700 mm (P1)	0,2327	1,9138	0,169	1,3979	3,6192	0,2174
2	500 mm (P2)	0,1274	1,378	0,0475	1,4239	2,9949	0,4606
3	500 mm (P3)	0,4393	2,5694	0,2468	1,8915	3,3774	0,3765
4	300 mm (P4)	0,249	2,391	0,1012	1,7554	4,578	0,3901
	Ø (1-4)	0,2621	2,0631	0,1411	1,6172	3,6424	0,3612

Fig. 3. Measurement setup for determining the accuracy of the Magic Leap 2

5 Discussion

Current AR tools have limited inspection applications and face challenges with time-consuming setup processes. Applications are missing for effective manual sensor guidance to enhance efficiency and reliability. This study introduces a novel AR application designed to streamline inspections in green aviation. The core contribution is a dedicated authoring tool, validated through developing and testing a functional inspector application, empowering users to create mobile, sensor-guided inspection procedures. Our modular AR authoring tool, designed for hydrogen leakage detection and rivet row inspection, addresses these issues by integrating various tracking technologies. It supports customizable inputs and combines marker-based and markerless localization for increased robustness. The study of usability suggests positive user feedback and the potential to enhance both the speed and quality of inspections, aligning with findings from previous research in the field [7]. However, challenges remain, particularly in handling complex trajectories and tracking with the HL2, limiting its use in leakage inspection. Real-time tracking is constrained by computational demands, affecting hologram placement and AR scene generation. To overcome these challenges, we tested the tool on the ML2, which demonstrated sufficient position accuracy for authoring of 1,39 mm.

For a reliable sensor-guided application for inspectors, further updates are required—an aspect beyond the scope of this study. The application restricts trajectory variations to basic shapes, limiting its applicability to a wider range of inspection scenarios. Incorporating freeform splines or shape templates would enhance the system's versatility. The current evaluation lacks real-world testing by experts. It involves a small, male-dominated sample group with a technical background, causing potential statistical outliers. The accuracy assessment aimed to evaluate performance using pipes as a background, as unstable tracking near pipes was noted. We utilized DIN-standardized calculations for static positions by EN ISO 9238 but did not fully implement the measuring procedure for full trajectory accuracy. Our results confirm that the ML2's lowest position accuracy of 1,87 mm is still sufficient for sensor guidance - given that human handling typically achieves around a centimeter accuracy. We also demonstrated that accuracy depends on factors like distance and angle, which are influenced by user handling and should be considered in inspector feedback.

Future work should incorporate more diverse studies across industrial scenarios to evaluate and optimize tracking accuracy, robustness, and inspection performance under real-world conditions. This will involve testing with actual tools, advanced sensor trajectories, and expert evaluations. Combining depth cameras with trained neural networks improves markerless object tracking accuracy through superior pose estimation. Given expert scarcity and associated costs, evaluating the reduction of authoring effort is critical for adoption. Therefore, AR trajectory creation must be compared with appropriate offline approaches. Our findings can serve as a basis for further comprehensive research to improve inspection quality through detailed analysis of inspector actions.

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References

1. Palmarini, R., Erkoyuncu, J.A.: A systematic review of augmented reality applications in maintenance. R. CIM **49**, 215–228 (2018). https://doi.org/10.1016/j.rcim.2017.06.002
2. Moenck, K., Koch, J., Rath, J.-E., Büsch, L., et al.: Industry 5.0 in Aircraft Production and MRO (2024). https://doi.org/10.13140/RG.2.2.33842.00961
3. Koch, J., Lotzing, G., Eschen, et al.: A human-centered IIoT platform approach for manual inspections. Procedia CIRP (2023). https://doi.org/10.1016/j.procir.2023.04.089
4. Marino, E., Barbieri, L., Colacino, B., et.al.: An AR inspection tool to support workers in I4.0 environments. C. i. I.(2021). https://doi.org/10.1016/j.compind.2021.103412
5. Apostolopoulos, G., Andronas, D., Fourtakas, N., Makris, S.: Operator training framework for hybrid environments: an augmented reality module using machine learning object recognition. Procedia CIRP **106**, 102–107 (2022). https://doi.org/10.1016/j.procir.2022.02.162
6. Lotsaris, K., et al.: Augmented Reality (AR) based framework for supporting human workers in flexible manufacturing. Procedia CIRP **96**, 301–306 (2021). https://doi.org/10.1016/j.procir.2021.01.091
7. Ong, S.K., Yew, A., Thanigaivel, N.K., Nee, A.Y.: Augmented reality-assisted robot programming system for industrial applications. Rob. Comput.-Integrat. Manuf. **61**, 101820 (2020). https://doi.org/10.1016/j.rcim.2019.101820
8. Sekhavat, Y.A., Namani, M.S.: Projection-based AR: effective visual feedback in gait rehab. IEEE HMS **48**(6), 626–636 (2018). https://doi.org/10.1109/THMS.2018.2877850
9. Zwick, M., Gerdts, M., Stütz, P.: Sensor-model-based trajectory optimization for UAVs to enhance detection performance. Sensors **23**, 664 (2023). https://doi.org/10.3390/s23020664
10. Bangor, A., Kortum, P.T., Miller, J.T.: An empirical evaluation of the system usability scale. Int. J. Hum. Comput. Interact. **24**(6), 574–594 (2008). https://doi.org/10.1080/10447310802205776