

Summary of the Doctoral Dissertation

# Tracking Head Movements in a Flight Simulator Environment using SLAM Mechanism of Augmented Reality Goggles

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The evolving complexity of modern aviation demands continuous advancements in pilot training technologies. This dissertation addresses a critical gap in flight simulation by developing and validating an innovative augmented reality (AR)-based head-tracking system that utilizes Simultaneous Localisation and Mapping (SLAM) technology, integrated with an adaptive Kalman-Particle filter fusion. By enhancing the fidelity, responsiveness, and realism of AR flight simulators, the research makes a transformative contribution to the aviation industry, leading to improved pilot training, increased operational safety, and heightened preparedness for real-world scenarios.

The motivation for this research stems from the pressing need to overcome the limitations of existing flight simulators, which often suffer from tracking inaccuracies, latency issues, and insufficient adaptability to dynamic cockpit environments. Flight simulators are indispensable in pilot training, allowing for the practice of complex manoeuvres, emergency scenarios, and diverse flight conditions in a safe, controlled environment. However, the effectiveness of these simulators is heavily reliant on the accuracy and responsiveness of the head-tracking systems that drive the AR interfaces. Current head-tracking technologies, including marker-based systems and inertial sensors, frequently encounter challenges such as drift, occlusion, and environmental noise. These limitations can lead to misalignment between virtual and physical elements, ultimately disrupting the immersive experience and reducing the effectiveness of training. Such constraints undermine the immersive quality of AR simulations, hindering pilots from fully engaging in prolonged, realistic training exercises. This thesis addresses these challenges directly by proposing a novel SLAM-based approach tailored to the specific requirements of flight simulation environments. SLAM technology enables real-time cockpit mapping, dynamically adjusting to head movements and environmental shifts, ensuring that virtual overlays remain consistently aligned with physical cockpit elements. This dynamic recalibration enhances pilot situational awareness, allowing fluid transitions between

simulated and real-world environments.

A comprehensive literature review highlights the deficiencies of existing marker and IMU-based tracking methods, establishing a foundation for integrating SLAM technologies. This research rigorously evaluates various SLAM algorithms, including ORB-SLAM, RGB-D SLAM, and Visual-Inertial SLAM (VINS). The selection and refinement of these algorithms play a crucial role in enhancing the robustness and accuracy of AR-based flight simulators. The integration of SLAM reduces latency and significantly improves tracking precision, addressing the core limitations of existing systems. In parallel, this dissertation provides a detailed comparison between marker-based tracking and SLAM-based tracking for flight simulators. While cost-effective and straightforward, Marker-based tracking often struggles with occlusion and drift, particularly in complex, multi-angle environments such as aircraft cockpits. SLAM-based tracking, by contrast, offers superior adaptability by continuously updating the environment's spatial map. This study evaluates the performance of both approaches across diverse flight scenarios, revealing that SLAM-based tracking consistently outperforms marker-based methods in adaptability, responsiveness, and overall immersion. The comparative analysis underscores SLAM's potential to revolutionize pilot training, enabling more realistic and uninterrupted AR experiences.

Complementing spatial fidelity, the research also develops a machine-learning identification layer that continuously and implicitly recognizes the trainee and their current task from routine AR interaction. A multimodal, multi-branch LSTM fuses time-synchronized eye-gaze, head-motion, and hand-gesture streams to derive stable behavioural biometrics for continuous authentication and task recognition on-device. This layer replaces cumbersome keyboard/PIN login on shared headsets, strengthens privacy and access control, and enables task-contingent personalization so overlays, checklists, and assessments are bound to the correct user and adapted in real time without interrupting training.

Extending adaptivity beyond identification, the dissertation contributes a light-weight deep-learning framework that predicts memory-retention state using non-invasive behavioural signals captured by HoloLens 2: gaze duration, interaction counts, revisit counts, and head-movement stability, augmented with content category embeddings. By inferring states such as strong recall or cognitive overload, the framework supports real-time pacing, targeted repetition, and scaffolded guidance, thereby closing the loop between how trainees interact and what they retain and advancing the goal of low-load, effective training.

The methodological framework of this research encompasses extensive experimental setups and comparative analyses of diverse filtering approaches, including Extended Kalman Filter (EKF), Unscented Kalman Filter (UKF), Ensemble Kalman Filter (EnKF), and Sequential Importance Resampling (SIR) particle filters. The innovative fusion of Kalman and particle filters is shown to leverage the complementary strengths of both approaches, addressing the nonlinear dynamics inherent to AR head tracking in flight simulation. This hybrid approach enhances the overall resilience and accuracy of the tracking system, resulting in superior stability during flight simulation exercises.

Experimental validations demonstrate that this adaptive fusion method consistently reduces the root mean square error (RMSE) across spatial tracking metrics, resulting in a notable increase in stability and precision.

Moreover, the research examines the impact of these technological advancements on the efficacy of pilot training. One of the most significant findings is the reduction in latency and motion sickness experienced during extended simulation sessions. Traditional flight simulators, which rely heavily on marker-based tracking, often suffer from delayed responses that can induce motion sickness in pilots. The refined tracking precision enabled by SLAM minimizes cognitive dissonance, allowing pilots to remain engaged in immersive training environments for more extended periods without discomfort. This breakthrough enhances training outcomes and promotes the cost-effective scaling of AR-based flight simulators for widespread adoption in commercial and military aviation sectors.

The thesis also contributes a novel adaptation of Fitts' Law for AR environments, offering a theoretical framework for evaluating user interactions in three-dimensional space. By incorporating head movements and spatial orientation into predictive models, this adaptation reduces interaction task difficulty by approximately 40%, thereby optimizing AR interface designs for an enhanced user experience. This insight paves the way for more intuitive cockpit interfaces and ergonomic AR system layouts, further reinforcing the simulator's value in comprehensive pilot training programs.

Beyond aviation, the platform's transferability is illustrated through an AR Mach-Zehnder Interferometer learning module that applies the same spatial, identity-aware, and cognition-adaptive design principles to concept-dense STEM content. The module converts abstract quantum-optics constructs into SLAM-anchored, manipulable representations of optical elements and beam paths and couples guided exploration with reconstruction to scaffold schema formation, establishing a reusable template for translating abstract technical knowledge into situated, task-guided interaction.

This dissertation represents a pivotal advancement in AR flight simulation by addressing core issues in head tracking, spatial mapping, and real-time interaction. The adaptive Kalman-Particle filter fusion method, combined with SLAM-based tracking, establishes new performance benchmarks for AR systems in aviation. This research lays the groundwork for future AR developments in flight simulation. It extends its applicability to other domains requiring high-fidelity spatial tracking, such as unmanned aerial vehicle (UAV) piloting and air traffic management. By bridging the technological divide between simulated and real-world flight environments, this dissertation underscores the transformative potential of AR in aviation, ushering in a new era of immersive, responsive, and effective pilot training solutions.