

South Dakota State University
2026 Gateway to Blue Skies Technical Paper – RepAir



WINGMAN

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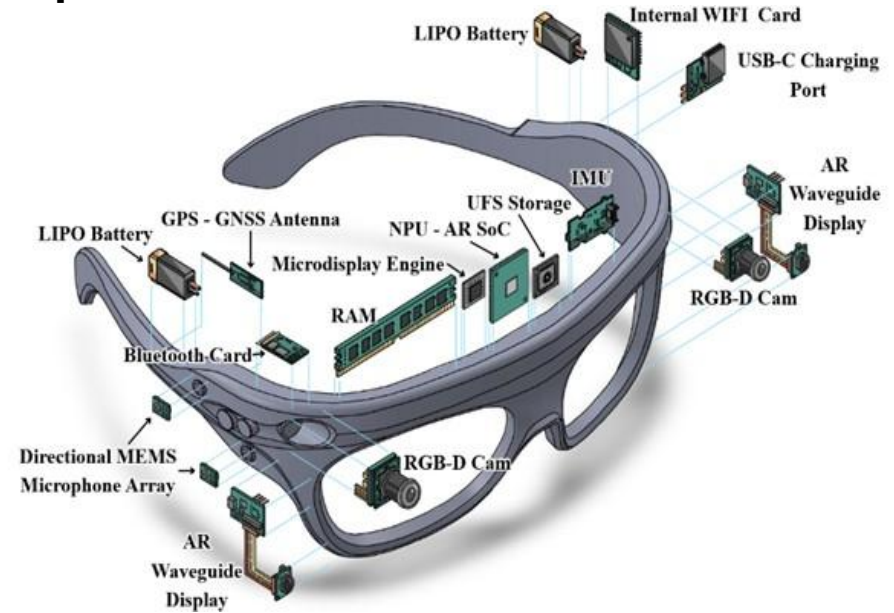
Todd Letcher



Project Summary:

- Focused on increasing technician efficiency and reducing documentation error in aircraft line maintenance by providing hands-free access to maintenance information and improving the speed and accuracy of maintenance logging.
- Overview:
 - Hands-free augmented reality (AR) safety glasses
 - WINGMAN offers three main functions:
 - Inquiry-Based Manual Referencing
 - Autonomous Reporting
 - Document photo-based Scrubbing
 - *Displaying relevant maintenance information based on user inquiries or fault codes from the airplane's computer.*
 - *Autonomous maintenance draft report compiled through voice recordings, pictures, and fault codes saved onto WINGMAN server.*
 - *Photographing a component retrieves matched historical maintenance reports and displays a semantic summary of recurring findings and ATA chapter references in the AR HUD.*

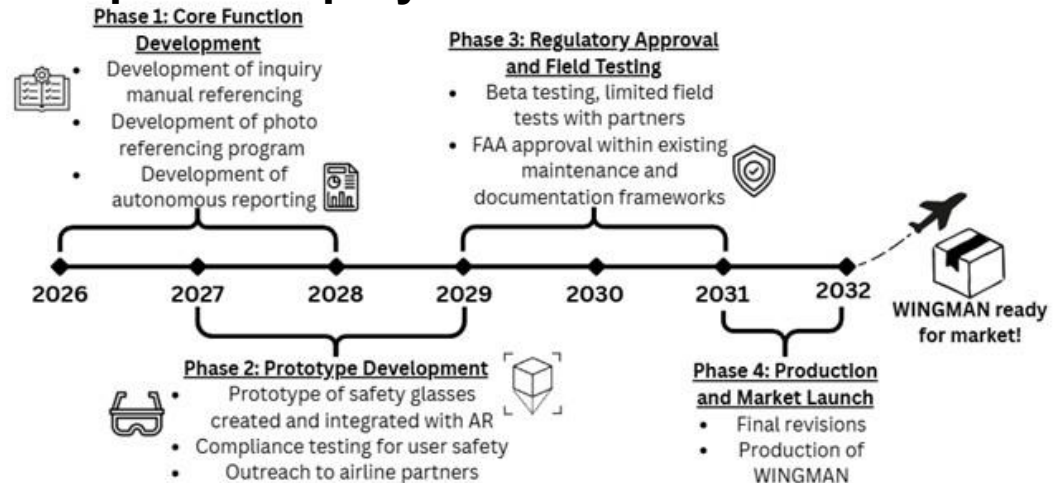
Concept:



Team Composition/Roles:

- **South Dakota State University**, Senior Design Team
- Team:
 - Owen Diede – Team Lead
 - Anders Olsen – Networking Lead
 - Matthew Wieberdink – Documentation/Programming Lead
 - Christian Lee – Design Lead
- Team qualifications for success:
 - Senior Engineering Students at South Dakota State University
 - Multiple Engineering Jobs/Internships
 - Skills Include: CAD, Manufacturing Processes, Research, Prototyping & Testing
 - Activities: Aerospace Club, Robotics Club, JEC, Biomedical Engineering Club, Society of Physics Students, Undergrad Research Students.

Proposed deployment timeline:



WINGMAN's core supporting technologies are already mature, with individual component TRLs ranging from 6–9 at the start of development. While AR and neural network integration represents emerging ground, the system is positioned at TRL 6 in 2026 and on track for TRL 9 by 2032.

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Abstract

Commercial aviation line maintenance relies on manual, task-diverting workflows for technical reference and documentation that consume an estimated 30% of a technician's shift, a figure validated through interviews with industry professionals and research data. These inefficiencies compound with the projected fleet growth of 2.4% annually to 5,700 U.S. aircraft by 2035, a shortfall of 48,000 maintenance technicians projected by the late 2020s, and over 1.2 million maintenance-related flight delays costing the aviation system \$33 billion annually. Current workflows require mechanics to physically disengage from the aircraft to navigate electronic technical manuals on fixed terminals or handheld devices and to recall and manually record inspection findings after the fact, introducing documentation gaps that contribute directly to 20.7% of maintenance-related incidents. These inefficiencies present a growing constraint on fleet scalability and technician capacity at precisely the moment the industry can least afford them. The proposed WINGMAN system is an augmented reality (AR) maintenance assistant in the form of ANSI Z87.1-compliant safety glasses made from polycarbonate and nylon. When used by certified aircraft mechanics, it delivers three core functions: hands-free voice-query access to electronic technical manuals, real-time autonomous report compilation through voice dictation, and history-based documentation scrubbing using onboard photo-similarity search. These functions will be performed through the glasses in a virtual workspace, enabling a technician to receive, review, and record relevant maintenance information. RGB-d cameras and an OLED waveguide module enable AR functionality, with semantic and photo similarity searches performed by integrated software models that are processed by a system-on-a-chip.

Unlike existing workflows, WINGMAN delivers reference material and captures inspection findings in parallel with hands-on maintenance work, eliminating task interruption entirely. Built from commercially available hardware and open-source software, WINGMAN integrates into existing airline workflows and regulatory frameworks without device-level FAA certification, requiring no changes to approved documentation systems and no modifications to existing recordkeeping infrastructure. Because of this, WINGMAN is estimated to have all components at a market-ready (TRL 9) level by 2032. A single technician utilizing WINGMAN generates an estimated \$60,835 in annual savings against a \$2,500 unit cost, a return that scales to millions of dollars across regional airline fleets. WINGMAN represents a scalable, non-disruptive advancement in aviation maintenance that keeps the authority in the hands of the certified mechanic while positioning the industry for a data-driven maintenance future. This paper expands the Phase 1 concept across multiple areas. The situation assessment is grounded in sourced workforce and financial data. The regulatory pathway is fully mapped, confirming no device-level certification is required. Cost and ROI analysis is rebuilt to cover the full scope of savings and losses, including a derived wholesale unit cost. The concept of operations is restructured into six subsections covering the mechanic's complete workflow, including training, reliability, and future use cases.

1.0 Situation Assessment

1.1 Industry Context

Inspections are among the most recurring and critical workflows in commercial aviation. Routine pre- and post-flight inspections occur under tight time constraints, requiring certified mechanics to reference applicable technical documentation, execute prescribed procedures, and produce a traceable maintenance log entry for each finding. These requirements extend beyond simply regulatory compliance. Documentation quality directly correlates with safety outcomes as poor or incomplete records impair future troubleshooting, obscure recurring defects, and create liability. A Federal Aviation Administration (FAA) commissioned study found that approximately 35% of maintenance reporting issues were paperwork-related, and 10% resulted in direct procedural changes [1].

The commercial aviation industry is experiencing significant growth, putting pressure on existing procedures. The FAA projects the U.S. commercial fleet will grow 2.4% annually from approximately 4,500 aircraft to 5,700 by 2035 [2]. Despite this growth, the maintenance workforce is not growing proportionally, with a projected shortfall of 48,000 maintenance technicians anticipated by the late 2020's [3]. As the aviation industry continues to grow with a pressured, constrained workforce, each mechanic will be expected to manage a growing number of inspections per shift, with less margin for workflow inefficiencies.

1.2 Documentation and Referencing Context

Today, line maintenance documentation and referencing rely on manual, task-diverting processes. Mechanics access approved Electronic Technical Manuals (ETMs) on handheld devices or fixed terminals, requiring them to stop hands-on work to navigate documentation [1]. For unexpected findings that may arise during inspections, locating the applicable procedure from scratch increases the cognitive load on the user and correspondingly increases the time demand. Interviews with Part 121-mechanics confirm that finding detailed procedural information in current workflows is a frequent source of delay, particularly for unusual fault codes or random findings outside of the mechanics' standard practices.

Post-inspection documentation compounds this inefficiency. Recalling findings from memory, sometimes hours after completing work, produces omitted steps, inconsistent phrasing, and incomplete records. This leads to further inefficiencies down the line as 20.7% of maintenance-related incidents are directly attributable to incomplete maintenance records [4]. These inefficiencies compound across an inspection cycle with multiple mechanics performing individual inspections and documentation, leading to significantly lower-quality documentation.

1.3 Financial Impact

The financial consequences of these inefficiencies are substantial and span across the entire industry. It is estimated that maintenance and ground crew errors alone cost two billion dollars annually, adjusted for inflation [5]. The Bureau of Transportation Statistics reports that maintenance issues contribute to over 1.2 million delayed flights annually in the U.S. [6]. At an average cost of \$100.76 per delayed minute with a mean delay of 28 mins, each event costs the airline approximately \$2,821 per delayed departure [7]. Issues that prevent departure carry much steeper costs, ranging from \$10,000-\$150,000 per hour, depending on aircraft type and route [8]. Across all causes, U.S. flight delays cost the entire aviation system \$33 billion annually [7]. Documentation errors that allow defects to be misrepresented or even omitted are direct contributors to both delay categories. Even marginal efficiency improvements, such as a 5% reduction in maintenance-related delays, would translate to \$1.6 billion in recovered value annually.

1.4 Current Practices and Their Challenges

While this gap has substantial room for improvement, prior solutions have addressed parts of it. Reference material has been digitized and applied to a Toughpad, providing a mobile electronic reference

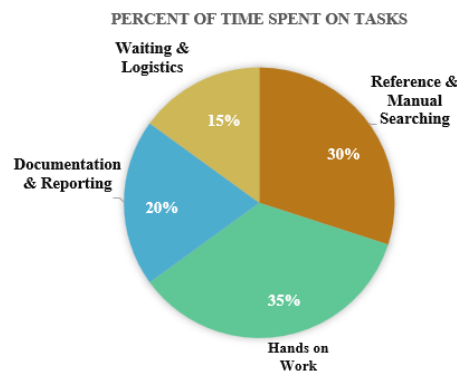


Figure 1: Mechanic task delegation breakdown [40, 41, 42]

system [9]. Further, Boeing's Project Juggernaut applied heads-up wiring diagrams to assembly, cutting production time by 25%, and GE Aviation's Google Glass implementation in engine maintenance achieved an 8–12% efficiency gain [10, 11].

These deployments demonstrate real value but do not address the full workflow gap present in line maintenance. Toughpads allow for digitization of reference material but do not eliminate task interruption. The mechanic is still required to stop hands-on work to navigate, read, and manually record findings, an issue directly addressed by WINGMAN.

The Boeing and GE tests were conducted in controlled factory environments against fixed procedural checklists; neither system captures autonomous report drafts, performs photo-based maintenance history retrieval, or operates offline. WINGMAN addresses this gap directly, combining all three functions in a single PPE-compliant form factor purpose-built for the variability and regulatory demands of line maintenance.

2.0 Use Case and Proposed Solution

2.1 Use Case

The primary use case for WINGMAN is commercial aviation line maintenance, specifically pre- and post-flight inspections with associated real-time documentation. This environment was selected because it represents the highest frequency of inspection and documentation demands under the tightest operational time constraints, presenting the greatest cumulative opportunity for efficiency improvement [12]. While this paper focuses on line maintenance, WINGMAN's architecture extends naturally to Maintenance Repair and Operations (MRO) heavy check facilities, technician training programs, and general aviation without requiring structural changes to the core system.

2.2 System Overview

WINGMAN is an augmented reality (AR) maintenance support system worn by a certified aircraft mechanic for inspection and maintenance tasks. The system is designed to increase technician efficiency and documentation quality through three core functions. Voice-input, query-based manual referencing provides relevant ETM content and procedural guidance through a hands-free HUD display, without requiring the mechanic to disengage from the aircraft. Autonomous reporting captures inspection findings through voice input and visual capture, compiling a structured draft maintenance log for the mechanic's review and approval. Documentation scrubbing uses onboard cameras and computer vision to identify prior maintenance records associated with the component being inspected, surfacing recent reports and recurring findings as a contextual snapshot at the start of each task. Across all three functions, WINGMAN operates as an advisory-only tool. Final authority remains with the certified mechanic at every step, avoiding device-level FAA certification requirements and eliminating any scenario where the system contributes to an unsafe outcome without human oversight.

2.3 Hardware Architecture

WINGMAN's hardware is assembled entirely from commercially available components, packaged in an ANSI Z87.1-compliant form factor that meets existing PPE requirements without adding bulk or requiring mechanics to wear secondary equipment [13]. The form factor is designed to be sleek, avoiding helmet or headset configurations, which add bulk and increase adoption friction. For mechanics with prescription eyewear, WINGMAN offers a bonded prescription fitted lens option fabricated by a third-party supplier, a method already used in commercial AR applications [14].

Input capture uses a stereo RGB-D camera array for depth perception, AR overlay anchoring, and documentation scrubbing, paired with a directional microphone array that isolates the mechanic's voice in hangar environments routinely exceeding 85 dB [15]. Processing runs on a commercial AR-grade System-on-Chip with a dedicated Neural Processing Unit, enabling sustained on-device artificial intelligence (AI) inference within a wearable form factor. An onboard inertial measurement unit (IMU) provides continuous head-pose estimation to stabilize AR overlays during hands-on movement, crucial for work environments. Local storage accommodates a full offline ETM index, maintenance history database, and draft report cache, ensuring core functionality without network connectivity. This functionality is consistent with

Toughpad workflows currently incorporated by Part 121 operators at locations without reliable terminal access [12]. The AR waveguide display delivers high-brightness output directly to the eye, maintaining readability in direct sunlight. With >80% lens transmittance, the mechanic's direct view of the aircraft remains unobstructed with AR rendering present [16].

2.4 Software Architecture

WINGMAN's software stack is built entirely on open-source libraries, eliminating licensing costs and reducing development burden. WINGMAN's core functionalities run through three pipelines, voice, vision, and data. Each operates fully on-device in offline conditions, syncing to network resources opportunistically.

The voice pipeline uses offline speech recognition fine-tuned for aviation-specific vocabulary, enabling hands-free command execution in network-isolated environments. ETM content is ingested across PDF, structured document, and scanned-page formats, sectioned by Air Transport Association (ATA) chapter, and converted to semantic vector representations using sentence transformer models. This approach will find contextually relevant procedures even when a mechanic's query does not match exact manual terminology, providing a significant advantage over keyword search [17]. The vision pipeline generates vector embeddings for an input image, representing the visual features of the image. This vector is then parsed against a local database of historical maintenance record embeddings from embedded images, allowing for rapid similarity retrieval. Software functionality allows WINGMAN to search across databases of up to 10 million vectors, allowing for multiple years of aircraft data to be stored and parsed [18]. Matched maintenance records are ranked by similarity score and then displayed in the AR HUD, allowing for visual report history lookup. Maintenance log drafts are assembled in a report structure engine that maps the user's

dictated findings to the associated fields of a maintenance log entry. This creates a text box displayed on the HUD with things such as description of work performed, date and time, aircraft identification number, ATA chapter, and the mechanic's certificate number. Each entry is editable with voice commands and navigated with buttons located on the side of the glasses. Upon approval, the completed draft is transmitted via HTTPS/TLS 1.3 to the airline's secure server, where it enters the standard review and approval workflow. This allows for post-submission editing of unwanted dictation and verification of draft content. No WINGMAN-generated content enters the official maintenance record without passing through an authenticated mechanic sign-off step, maintaining regulatory compliance with 14 CFR Section 43 Part 9 and the data integrity standards of AC 120-78B [19, 20].

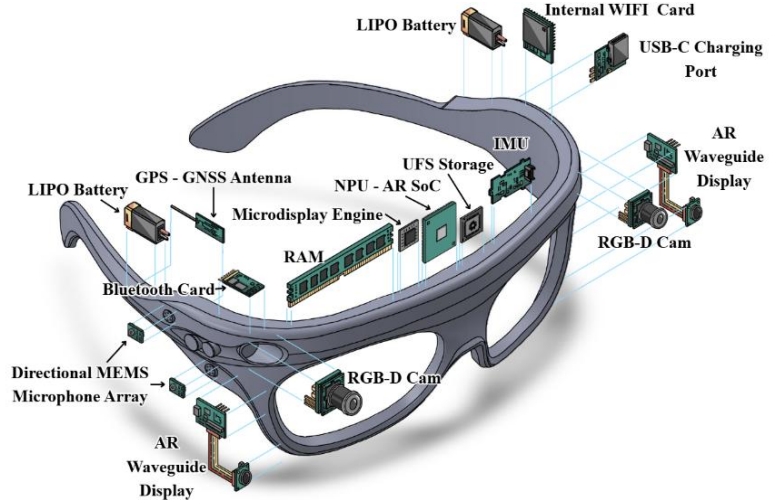


Figure 2: WINGMAN hardware breakdown



Figure 3: AR HUD Mockup [43, 44]

2.5 Key Design Principles

Three principles govern WINGMAN's architecture. Advisory-only authority ensures every maintenance action is a technician-reviewed recommendation and never a directive, preserving certified technician decision-making and eliminating liability from unsupervised outputs. Offline-first operation ensures all three core functions run without network connectivity, making WINGMAN available at remote stations and in poor network environments. An intentional lack of hardware integration with the aircraft eliminates any scenario in which WINGMAN affects airworthiness and simplifies the regulatory pathway.

2.6 TRL

WINGMAN's development builds on proven technologies across four functional subsystems (Table 1). No subsystem requires a fundamental scientific discovery, every component is already deployed at commercial or industrial scale, and the remaining work is aviation-specific integration and optimization rather than novel invention.

The AR and Human Interface Subsystem sits at a TRL 6-7, comprised of proven individual components: the OLED waveguide display (TRL 8), Bluetooth and WiFi connectivity (TRL 9), and head pose tracking (TRL 7). The remaining work to reach TRL 9 is optimization for extended use environments and IMU-based head pose tracking refinement for stable HUD overlay anchoring.

The Computer Vision subsystem sits at TRL 6 with all components proven in other use cases, but requires product-specific optimization. This encompasses RGB-D depth sensing (TRL 6), the visual vector embedding and retrieval pipeline, which the team has physically implemented and validated against 80+ historical maintenance records, confirming functional retrieval performance ahead of hardware integration (TRL 8) and depth-based spatial mapping (TRL 7). The primary remaining work to reach TRL 9 is outdoor and hangar environment validation of depth-based spatial mapping, along with aviation-specific training data for object recognition and image similarity retrieval.

The system and infrastructure subsystem is the most mature, with every component residing at a TRL 7-9. Offline operation, HTTPS-encrypted server synchronization, ETM document ingestion, and vector database technologies are all industry-proven technologies ready for production. The primary remaining task to achieve TRL 9 is optimizing edge computing, the execution of processing workloads directly on the wearable device rather than offloading to a remote server, within the wearable form factor.

The information and AI subsystem sits at a TRL 7, with all core components proven in commercial deployments. The Vosk offline speech recognition engine (TRL 8) is a production-ready library with demonstrated accuracy in field environments, requiring only aviation-specific vocabulary fine-tuning to reach TRL 9. Sentence transformer-based semantic search (TRL 7) is mature at the component level, with the remaining work being domain-specific training on ATA chapter nomenclature and maintenance terminology. The autonomous report drafting engine (TRL 7) requires formatting compliance with FAA documentation standards to reach TRL 9.

The overall system TRL is governed by its lowest-maturity integration-critical components, placing WINGMAN at TRL 6 in 2026. As aviation-specific training, hardware integration, and domain validation are completed across Phases 1 through 3, the system advances to TRL 9 by 2032, three years ahead of the 2035 implementation goal.

Table 1: Subsystem Technology Readiness Levels

Subsystem	Key Components	TRL	Primary Remaining Work
AR and Human Interface	OLED micro-display, IMU head tracking, Bluetooth	6	Extended-wear ergonomic validation; depth sensing and tracking refinement for active maintenance environments
Computer Vision	RGB-D stereo camera array, 3D depth mapping, object recognition, visual embedding, image similarity retrieval	6	Aviation-specific lighting calibration, angle variability testing, and industrial deployment validation
System Infrastructure	Offline operation, server/cloud sync, FAISS vector database, edge computing, offline-first architecture	7	Wearable form factor optimization for edge compute; FAISS specialization for aviation maintenance datasets
Information and AI	Vosk speech recognition, NLP, OCR, PDF/document ingestion, ATA chapter search, autonomous report drafting, voice-editable log entry	7	Aviation vocabulary specialization, FAA documentation format compliance, and manual revision currency

Table 2: Subsystem technology readiness level yearly progression

Subsystem	TRL Timeline						
	2026	2027	2028	2029	2030	2031	2032
AR and Human Interface	6	6	7	7	8	8	9
Computer Vision	6	7	7	7	8	8	9
System Infrastructure	7	7	7	8	8	8	9
Information and AI	7	7	8	8	8	8	9

3.0 Concept of Operations

3.1 Pre-Use Setup

Before deployment, WINGMAN connects to the airline's secure server to sync its offline ETM index and maintenance record embeddings to local storage. This process requires no modifications to the airline's existing documentation structure. ETMs are ingested in their current format, and maintenance records are indexed without altering source files. Each mechanic registers their FAA Airframe and Powerplant certificate number to their device profile, creating an audit trail that attributes every WINGMAN action to a specific certification. This certificate tagging satisfies 14 CFR Part 43 Section 43.9 compliance requirements and creates a complete activity log that can be reviewed in the event of an incident, FAA audit, or liability dispute. [19].

At the start of each shift, the mechanic retrieves WINGMAN from the tool crib charging station. Upon activation, WINGMAN performs a background sync to pull ETM revisions and updated maintenance records since the last session, then confirms the mechanic's certificate number and the tail number of the aircraft being worked, tying all outputs to aircraft-specific material and the mechanic's certification.

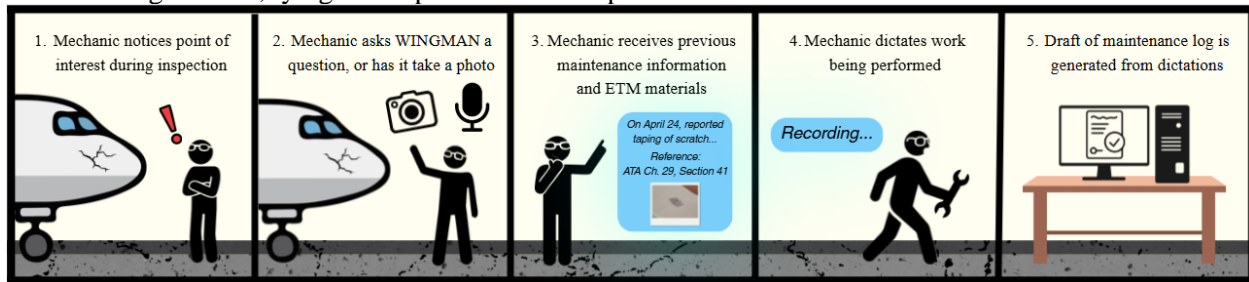


Figure 4: WINGMAN concept of operations

3.2 Documentation Scrubbing

As inspection begins, the mechanic photographs any component or point of interest that requires immediate action. WINGMAN's vision pipeline generates an embedding from the image and searches against the local index of historical maintenance record embeddings, returning the five most similar prior reports in the AR HUD. A semantic summary of recurring descriptions and ATA chapter references found across those reports is displayed beneath the report list, providing the mechanic with a contextual snapshot of prior actions taken on similar findings before any hands-on work begins. The FAA has identified situational awareness enhancement as one of the primary operational benefits of head-worn technology in aviation maintenance, something documentation scrubbing directly provides [21].

3.3 Inquiry-Based Manual Referencing

Following documentation scrubbing, the mechanic can issue voice queries to access procedural information at any point during the inspection. The voice query is transcribed on-device by the offline speech recognition engine, encoded into a semantic vector by the sentence transformer, and matched against the pre-built ETM embedding index via Facebook AI Similarity Search (FAISS). The system returns the most contextually relevant procedural information in the AR HUD, stabilized by the IMU, so content remains readable during physical movement. Because semantic retrieval is used rather than keyword search, mechanics can describe a finding in plain language and still surface the correct procedure. This reduces cognitive load, particularly for non-routine findings outside a mechanic's standard practice [22]. Voice commands allow the mechanic to navigate results, request new searches, and close the panel without interrupting hands-on work.

3.4 Autonomous Reporting

As the mechanic completes each inspection step or identifies a finding, observations are dictated into WINGMAN for autonomous report compilation. The voice pipeline converts speech to structured text, mapping findings to their corresponding fields. This includes the description of work performed, date, aircraft identification, ATA chapter, and mechanic certificate number, all displayed as an editable HUD panel navigable by voice or temple-arm buttons. As a recommended best practice, mechanics can optionally

embed photographs into report sections via the camera array for added visual documentation. Once complete, the mechanic reviews the full draft, corrects any misrecognized terms, and provides explicit approval before submission. The entry is then transmitted via HTTPS/TLS encrypted connection to the airline's recordkeeping server, entering the standard review workflow. No WINGMAN-generated content enters the official maintenance record without authenticated mechanic sign-off, maintaining compliance with 14 CFR Part 43 Section 43.9 and AC 120-78B [19, 20].

3.5 Overall System Integration

WINGMAN interfaces with two existing airline infrastructure components, the ETM library and electronic recordkeeping server, on a read and draft-only basis, requiring no changes to approved documentation systems, no new server infrastructure, and no modification to source manuals. The only administrative actions required upon implementation are certificate registration and API key assignment, both managed by the airline's existing IT and maintenance teams. Together, these integration points ensure WINGMAN augments existing airline workflows without requiring procedural, infrastructural, or documentation changes from any stakeholder.

4.0 Path to Deployment

4.1 Deployment Timeline

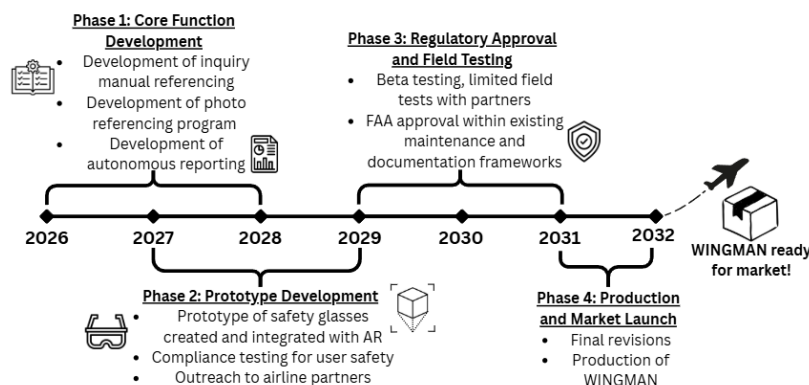


Figure 5: Four-phase path to deployment timeline

The timeline for the production of WINGMAN is broken into four distinct phases. Phase 1 (2026–2028) focuses on software development and validation of all three core functions in a development environment. Manual referencing and documentation scrubbing are prioritized first, establishing the ETM indexing and FAISS vector database foundation. Autonomous reporting follows, building on the voice pipeline established in the first stage.

Phase 2 (2027–2029) integrates validated software into a physical prototype, conducting ANSI Z87.1 compliance testing and aviation-specific optimization across vocabulary recognition, HUD layout, and vector search performance. OEM research and development access programs will be pursued during this phase to support development and optimization prior to full airline partnership, requiring a formal business relationship and NDA. Additionally, initial FAA outreach is pursued within this phase, five years ahead of the 2032 market launch. This provides a substantial lead time for interpretive clarifications.

Phase 3 (2029–2031) pursues FAA A025 amendment approval through partnered airline Principal Maintenance Inspectors, while conducting live field testing to validate system performance in operational environments. Prior FAA contact from Phase 2 is targeted to compress this timeline.

Phase 4 (2031–2032) completes final revisions based on field data and initiates production. Previously established partnerships with airline partners who participated in Phase 3 provide the infrastructure for a rapidly expanding market across additional carriers. With these accelerations, WINGMAN should be

market-ready by late 2031 or early 2032, providing a highly accelerated pathway to full development and implementation earlier than the overall 2035 goal.

4.2 Regulatory Pathway

WINGMAN's AR glasses form factor carries no device-level FAA approval requirement. According to a Front-Line Maintenance Manager at the Fargo Flight Standards Office, there is currently no specific regulation governing AR wearable devices in a maintenance support context. No Supplemental Type Certificate (STC) is required as 14 CFR Part 21 Section 113 requires an STC only when a person introduces a major change in type design to a type-certificated product [23]. DO-178C and DO-254, the FAA-accepted standards for software and electronic hardware assurance in airborne systems, do not apply, as both standards govern airborne systems exclusively and WINGMAN operates entirely on ground personnel with zero hardware integration with the aircraft [24, 25]. In regulatory standing, the glasses are equivalent to a mechanic's safety goggles or a handheld flashlight.

Title 14 CFR Part 43 Section 43.9 sets the content requirements for any maintenance record entry, requiring the description of work performed, date, name, and certificate number of the performing mechanic [19]. Part 121 Sections 380 and 369 further require commercial carriers to maintain records under an FAA-approved maintenance manual [26, 27]. WINGMAN and this proposal have been created with these sections in mind to ensure compliance with existing standards. WINGMAN's HTTPS-encrypted, certificate-number-tagged draft records are designed to meet the data integrity, accuracy, and accessibility standards of AC 120-78B [20]. Airlines integrating WINGMAN would work with their Principal Maintenance Inspector to include WINGMAN-generated drafts within their existing Operations Specification A025 authorization [20]. This is an amendment to an existing approval, not a new certification process. A025 is required for electronic documentation approval, meaning WINGMAN slots into an already-approved framework without requiring independent regulatory action.

The cameras and microphone integrated into WINGMAN do not trigger any FAA regulatory requirement, as these sensors operate on ground personnel, not on airborne systems. More critically, the TSA-approved Airport Security Program under 49 CFR Part 1542 governs devices used in Security Identification Display Area (SIDA) and Air Operations Area (AOA) environments [28]. WINGMAN's design directly addresses this by limiting image capture and voice commands to be mechanic-initiated rather than continuous, processing audio locally on-device rather than externally, and HTTPS encrypting all transmitted data to the airline's own secure server. Further audio recording consent requirements under the federal wiretap act (18 U.S.C. Section 2511) and applicable state consent laws would be addressed in the standard employment policy at the time of airline deployment [29].

4.3 Barriers and Risk Mitigation

Interpretation of WINGMAN's classification could slow down adoption, as certain airlines or government bodies could apply additional scrutiny to the A025 amendment request. To counteract this, contact with the FAA will be made 5 years prior to the targeted market launch, providing substantial lead time to address any interpretive clarifications that may arise.

Cybersecurity risks associated with access to proprietary ETMs, maintenance records, and component photographs are addressed architecturally. All server-to-glasses data uses HTTPS/TLS 1.3 encryption. Each device is assigned a unique API key tied to the device hardware and mechanic certificate number, allowing instant server-side revocation if a device is lost or decommissioned. These controls are consistent with TSA cybersecurity directives and IATA security standards already mandated across airline digital infrastructure. [30, 31].

Workflow resistance is an inherent challenge for any tool introduced into aviation maintenance, where procedures are revised incrementally and mechanics are trained to follow them precisely. WINGMAN addresses this by positioning itself as a supplement to existing workflows rather than a replacement, requiring no procedural changes from mechanics and no modifications to approved documentation systems. Original Equipment Manufacturer (OEM) manual access is resolved through existing airline ETM licensing agreements, which can be extended to cover WINGMAN without requiring independent OEM negotiation during development.

Line maintenance occurs across a wide range of environmental conditions, including direct sunlight, rain, and dusty hangar environments. A high-brightness OLED waveguide display maintains readability in direct sunlight with a panel brightness of 5000 nit [16]. A polycarbonate nylon frame provides the impact durability required of PPE in active maintenance settings, and the form factor is designed to meet IP54 dust and moisture resistance ratings standard for industrial AR devices deployed in comparable field environments [32].

4.4 Training and Reliability

Because WINGMAN is advisory-only, technician onboarding is achievable within a single shift, covering HUD symbology, system limitations, and operative functions. A train-the-trainer model deploys lead technicians at each maintenance station to handle subsequent onboarding, enabling scalable rollout without centralized training infrastructure.

Routine upkeep consists of lens cleaning between shifts and periodic inspection of the frame and camera array for any physical damage. In the event of damage or component failure, WINGMAN’s part-independent construction allows for individual replacement of components, such as a battery replacement, microphone, or camera lens, without full unit replacement, reducing lifecycle costs and downtime.

4.5 Cost and ROI

Table 3: Single user annual return on investment

Savings Category	Time Savings (Hours)	Annual Savings
Inspection & Reporting Time	90	\$4,174.20
Reworks	18	\$834.84
Delays	1.5	\$9,028.10
AOG Duration	0.6	\$48,000.00
Unnecessary Movement	36	\$1,669.68
Cost of Glasses	N/A	-\$2,500.00
Onboarding	-8	-\$371.04
TOTAL ANNUAL SAVINGS	138.1	\$60,835.78

Prior AR maintenance deployments establish a performance baseline for WINGMAN benchmark estimates. In one study, a 75% reduction in procedural errors was noted when comparing AR-supported workflows over paper-based methods [33]. Furthermore, industrial deployments of AR document repair time reductions of up to 40% [34]. WINGMAN’s savings estimate a deliberately conservative 20% improvement factor across applicable categories and applies an hourly wage of \$46.38 for mechanics in scheduled air transportation (line-maintenance) [35].

With an estimated wholesale unit cost of \$2,500, a single WINGMAN user generates approximately \$60,835 in annual savings across five categories, detailed in Table 3. Each category reflects a direct connection between WINGMAN’s core functions and a measurable financial inefficiency in current line maintenance workflows.

Inspection and reporting efficiency savings account for \$4,174 annually, based on a time reduction of 20% across 1,800 annual tasks, derived from documented line maintenance frequencies of every 24–60 flight hours and validated through interviews with Part 121-certified mechanics [36]. The current process requires mechanics to stop hands-on work entirely to navigate documentation or record findings. WINGMAN eliminates this interruption by delivering information and capturing findings in parallel with active maintenance work.

Rework reduction contributes \$834 annually. When mechanics proceed from memory or a partial reference, steps can be missed or incorrectly sequenced. By surfacing the correct procedure at the moment it is needed, WINGMAN reduces rework events by the previously estimated 20% and increases overall efficiency.

Reduced flight delay duration yields \$9,028 per technician annually, representing the most direct and visible link between WINGMAN’s functionality and airline financial performance. At \$100.76 per delayed minute and a mean delay of 28 minutes, each maintenance-related delay costs approximately \$2,821 per

departure [7]. Faster access to fault documentation and more complete real-time reporting allows downstream teams to act more immediately, reducing both the frequency and duration of maintenance-related delays.

AOG event reduction accounts for \$48,000 annually, the largest single driver of savings. At an average cost of \$80,000 per AOG hour and an average AOG event duration of three hours, conservatively estimating each mechanic contributes to three cumulative AOG hours of downtime annually, a 20% reduction through improved documentation quality and faster fault data access represents a substantial return on investment [8, 37]. The ability to surface real-time maintenance history through documentation scrubbing directly addresses the procedural confusion and documentation gaps that contribute to these high-cost events.

Elimination of unnecessary movement between the work area and reference terminals contributes \$1,669 annually. Estimating 40% of 1,800 annual inspections require a 3-minute round trip, this amounts to 36 hours of lost labor per technician per year. This is an overlooked statistic, but one that compounds across a fleet.

Onboarding is estimated at a one-time cost of \$371.04, reflecting 8 hours of technician time at the hourly wage of \$46.38.

Considered only against structural inefficiencies independent of human error, WINGMAN recovers \$12,913 per technician annually against a \$2,500 upfront cost. Accounting for all savings, WINGMAN's return on investment increases to \$60,835. Scaled across even a modest regional airline, the proposed savings reach hundreds of thousands of dollars annually; for a larger company such as Delta, employing WINGMAN across their 6,647 AMT's would return annual savings of \$402,000,000 [38]. Approximately 75,000 employees registered to U.S. commercial airlines equates to a total addressable market of approximately \$187.5 million in potential revenue at a \$2,500 unit cost [39].

4.6 Future Additions

WINGMAN's initial deployment targets line maintenance, but its architecture positions it as a platform for a significantly broader maintenance ecosystem. The system's three core functions extend naturally into MRO heavy check facilities, technician training programs, and general aviation without architectural redesign, addressing the same efficiency gaps in environments where procedure complexity, documentation volume, and knowledge variability are even greater. Looking further, the structured inspection data WINGMAN generates with every use represents an asset that grows in value over time. Aggregated across fleets, this data positions WINGMAN as a predictive maintenance data collection infrastructure. WINGMAN would be able to assist in the identification of recurring issues with an aircraft, flag inspection patterns that precede failures, and identify component trends that indicate failure. At scale, WINGMAN evolves from a single-technician efficiency tool into a maintenance efficiency platform.

5.0 Expanded Analysis

The Phase 1 proposal identified the core problem and proposed a viable solution across several areas that judges and the team identified for deeper development in the final paper.

Judges noted it was unclear how WINGMAN interfaces with existing airline servers and compliance systems, and what FAA approval is required. The Regulatory Pathway section now maps a complete, sourced compliance pathway, no STC required, DO-178C and DO-254 do not apply to ground-worn devices, and recordkeeping integration is limited to an A025 amendment within a framework already held by major U.S. carriers. System integration with existing ETM libraries and recordkeeping servers is detailed in Section 3.5, confirming read and draft-only access requiring no infrastructure changes. OEM manual access is resolved through existing airline ETM licensing, as WINGMAN reads from the airline's locally hosted, already-licensed ETM database without independently reproducing or distributing proprietary content.

Judges requested commentary on maintenance, reliability, and prescription accommodation. Section 4.4 now addresses technician onboarding, a train-the-trainer rollout model, routine upkeep, and component-level repairability. Mechanics requiring prescription eyewear are accommodated through a prescription-fitted bonded lens option, using third-party optical suppliers established in the AR market.

Judges noted the absence of cost estimates and flagged environmental limitations. Section 4.5 now derives a \$2,500 wholesale unit cost from a component-level hardware and software table (shown in appendix A), with all ROI categories rebuilt from sourced industry data and full calculations provided in Appendix C. Section 4.3 explicitly addresses outdoor and hangar operating conditions, confirming a 5,000-nit display for direct sunlight readability and IP54 dust and moisture resistance.

Judges encouraged the team to think bigger regarding applicability. Section 4.6 establishes WINGMAN's natural extension into MRO heavy check facilities, technician training programs, and general aviation, and frames the long-term vision of WINGMAN as a predictive maintenance data platform aggregating structured inspection records across fleets.

Beyond judge feedback, the Situation Assessment was elevated from observation to evidence, adding FAA-projected fleet growth, a sourced 48,000-technician shortfall, BTS-reported delay figures, and a new Financial Impact subsection establishing \$33 billion in annual system-wide costs. An Existing Solutions subsection was added, benchmarking WINGMAN against prior deployments. The ConOps was restructured from a single flowchart into six dedicated subsections covering the mechanic's full workflow, with full hardware and software architecture documentation added in the appendix.

6.0 Conclusions and Key Findings

Commercial aviation maintenance is under compounding pressure from growing fleets and a projected shortage of 48,000 technicians, with a workforce still relying on manual, task-diverting workflows that consume up to 30% of every technician's shift [40]. Maintenance issues contribute to over 1.2 million delayed flights annually, \$33 billion in system-wide costs, and documentation errors that directly contribute to 20.7% of maintenance-related incidents. This growing problem presents a substantial need for efficiency improvements.

WINGMAN addresses this gap through a technically mature, regulatory-compliant system deployable without disrupting existing workflows or requiring device-level certification. Built from commercially available hardware and open-source software, the system reaches TRL 6 today with a clear pathway to TRL 9 by 2032, well within the 2035 target. With the technician shortage arriving in the late 2020s, the window for deployment makes the 2032 market-ready target not just feasible but necessary. WINGMAN presents a long-overdue upgrade for the commercial maintenance industry, delivering immediate, measurable efficiency gains and closing a critical gap in line maintenance workflows. With a proven regulatory pathway, mature technologies, and a deployment three years ahead of the 2035 target, WINGMAN positions itself as an actionable solution unlike concepts that require novel certification or introduce unproven hardware, slotting into operational infrastructure with a cost that is recovered in just weeks of deployment.

Key Findings:

- \$60,835 in annual savings per technician against a \$2,500 unit cost, scaling to \$402M annually for a company like Delta.
- No device-level FAA certification required; pathway limited to an A025 amendment.
- Advisory-only architecture preserves certified mechanic decision-making at every step, requiring no workflow changes.
- Safety glasses form factor functions as required PPE, eliminating adoption resistance.
- A conservative 5% reduction in maintenance delays recovers \$1.6 billion in annual system-wide value.

Appendices

Appendix A: Hardware and Software

Input Capture		
Component	Function	Cost
RGB-D Camera array	Depth perception for AR displaying and image capture	\$ 169.00
Four-element MEMS microphone array	Captures voice commands and dictated reports	\$ 20.00

Power and Connectivity		
Component	Function	Cost
2x 3.7 V, 5000 mAh lithium-polymer battery	Battery for system	\$ 44.00
Power Management IC	Charging and component power distribution	\$ 6.00
USB-C port	Charging and data transfer	\$ 2.00
WiFi/Bluetooth antenna	Wireless capability	\$ 7.00

Processing and Memory		
Component	Function	Cost
Qualcomm Snapdragon XR2 Gen 2 System-on-Chip	CPU, GPU, image signal processor, and dedicated Neural Processing Unit	\$ 84.00
Samsung Flash UFS 3.1 Storage (256 GB)	Storage for offline ETM index, FAISS vector database, draft reports, and photo captures	\$ 15.00
NVTEK System Memory - RAM (16 GB)	Quick access processing storage	\$ 44.00

Display and Form Factor		
Component	Function	Cost
OLED waveguide module	AR display system	\$ 899.00
Nylon frame + polycarb lens	Safety, comfort, and ANSI compliant	\$ 20.00

Appendix B: TRL of Hardware/Software Components

Appendix A — Hardware Technology Readiness Levels		
System Component	TRL	Reasoning
Micro Display (OLED)	8	Commonly used in phones, cameras, AR, and VR.
Depth Sensing (Stereo vision)	6	Used in AR and VR components.
Eye / Head Tracking	7	Used in VR for years now. Getting more advanced with AR.
Text to Speech	8	Text to speech is commonly used, but has not been specialized for maintenance environments.
Wireless Communication (Bluetooth)	9	Used commercially and in consumer products.
Offline Operation and Information Sync	9	Mature technology, used commercially and by consumers.
Server Backing / Cloud Backing	9	Common practice in many industries.
Edge Computing	7	Used in industry, would need optimization for wearable technology.
Object Recognition	6	Technology exists, but needs more development and optimization.
3D Depth Mapping	6	Technology exists, but is not fully developed / optimized for any use case.
3D Location Tracking	6	Technology exists, works in controlled environments. Testing for commercial aviation needed.
Advanced Search and AI Referencing	7	AI referencing is a proven concept.
Image Similarity Identification	6	Proven, but lighting and angles play factors.
Photo Embedding and Data Tagging	7	Commonly used for a few years in face scanning recognition.
Natural Language Processing	8	Already been used in Python for some time.

Appendix B — Software Technology Readiness Levels		
System Component	TRL	Reasoning
Vosk Offline Speech Recognition	8	Vosk is already used in many devices, but has not been specialized to the aviation environment and use cases.
Local Audio Pipeline	8–9	Mature technology with several libraries specializing in proximity text to speech.
PDF / Document Ingestion (pypdf, PyMuPDF, python-docx)	9	Mature capability with many libraries supporting it.
Optical Character Recognition	7–8	OCR is nearly a matured technology. It currently is used in many industry applications, but OCR still has some areas where issues can occur.
Embedding-Based Document Searching	7	This technology is proven, but validation and precision of searches may need further development.
ATA Chapter / Reference Searching	7	Straightforward and practical, but has issues in keeping up to date with yearly manuals / revisions.
MobileNetV3 Component Recognition	8	The MobileNetV3 software is proven and ready for use upon purchase, may need further specialization and development for aviation environments.
XR2 Edge Inference	8–9	Edge inference is used in many applications, and is a mature technology. Has not been specialized to our use cases.
3D / Visual Embedding-Based Part Identification	6	3D mapping technology has been proven with prototypes, but the technology needs further development before efficient industrial use.
FAISS Vector Database Search	8	FAISS is commonly used in many industry applications. Mature technology that is capable of large datasets. Has not been specialized for our uses yet.
Maintenance History Visual Match Retrieval	6	Visual photo embedding has been proven in prototypes and specific environments, but needs further development for consistent use and success.
AR HUD Record Display	6–7	AR displays are under development. They are seeing use in industry but have not been developed for long term comfortable easy use.
Autonomous Report Drafting Engine	7–8	Autonomous drafting technology is proven and used in many industries. The technology needs further specialization and verification for the aviation industry.
Voice-Editable Log Entry Creation	7	These technologies are mature, but have not been specialized for the aviation environment. Autonomously meeting FAA standards for documentation may be an issue.
Offline-First Edge Architecture	8–9	Local computing is commonly used and practiced, especially in the defense industry. Technology is mature.

Appendix C: Cost and ROI Calculations

Savings Category	Assumption (Per Single User)	Time Savings (Hours)	Annual Savings
Inspection & Reporting Time	1,800 tasks a year, 15 minutes per task, 20% time reduction, average mechanic salary of \$46.38 / hr	90	\$4,174.20
Reworks	1,800 tasks, 5% of tasks require rework, 20% time reduction, reworks take 1 hr, average mechanic salary of \$46.38 / hr	18	\$834.84
Delays	\$100.76/ minute cost for delay, avg delay 28 min, 16 delays per maintenance worker * 20% reduction	1.5	\$9,028.10
AOG Duration	Each mechanic contributes to 3 hours annually reduced by 20%, \$80,000 per hour AOG,	0.6	\$48,000.00
Unnecessary Movement	Conservatively 40% of tasks require movement to access reference data, 1800 annual tasks (720 trips), 3 mins round trip, \$46.38 / hr	36	\$1,669.68
Cost of Glasses	See cost calculation; adding approx. \$1300 for manufacturing processes and profit margin	N/A	-\$2,500.00
Onboarding	8 hour program for the mechanic	-8	-\$371.10
TOTAL ANNUAL SAVINGS		138.1	\$60,835.71

a) Inspection & Reporting Time savings

$$\left(\frac{1800 \text{ tasks} * 15 \text{ minutes} * 0.2 \text{ percentage}}{60 \frac{\text{minutes}}{\text{hour}}} \right) * \$46.38 \text{ hourly wage} = \$4,174.20$$

b) Reworks savings

$$(1800 \text{ tasks} * 0.05 \text{ percentage of tasks require rework} * 1 \text{ hour} * 0.2 \text{ percentage savings}) * \$46.38 \text{ hourly wage} = \$834.84$$

c) Number of delays per mechanic

$$\frac{1,200,000 \text{ flights delayed due to maintenance}}{75,000 \text{ commercial mechanics}} = 16 \text{ delays/mechanic}$$

d) Delays savings

$$\frac{\$100.76}{\text{min}} * \frac{28 \text{ mins}}{\text{delay task}} * \frac{16 \text{ delay tasks}}{\text{person} * \text{year}} * 0.2 \text{ percentage reduction} = \$9,028.10$$

e) AOG Duration savings

$$\begin{aligned} & \$80,000 \text{ per hour AOG cost} * 0.2 \text{ percentage savings} * 3 \text{ hours of AOG contribution} \\ & = \$48,000 \end{aligned}$$

f) Unnecessary Movement savings

$$\left(\frac{1800 \text{ tasks} * 3 \text{ minutes} * 0.4 \text{ percentage walking}}{60 \frac{\text{minutes}}{\text{hour}}} \right) * \$46.38 \text{ hourly wage} = \$1,669.68$$

g) Cost of glasses

$$\begin{aligned} & \$1,266 \text{ component costs} + \$300 \text{ assembly costs} + \$934 \text{ (37 \%) profit margin} \\ & = \$2500 \end{aligned}$$

h) Onboarding Losses

$$8 \text{ hour program} * \$46.38 \text{ hourly wage} = \$371.10$$

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