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Augmented Reality Systems for Skill-Based Digital Training

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ABSTRACT

Augmented reality (AR) overlays digital information -- step-by-step instructions, 3D component annotations, safety alerts, and performance feedback -- onto the real-world training environment, enabling hands-on skill development with real equipment while providing contextual digital guidance unavailable in traditional instruction. Unlike virtual reality's fully immersive simulated environment, AR preserves physical task engagement -- trainees use real tools, feel real materials, and develop genuine muscle memory -- while digital overlays reduce cognitive load from instruction lookup, prevent errors through real-time verification, and provide immediate corrective feedback. This paper proposes the AR Skill Training Evaluation Framework (ARSTEF), a systematic evaluation of five AR system architectures -- smart glasses (OST-AR), handheld tablet AR, projected AR, wearable wrist AR, and AI-enhanced spatial AR -- across six skill training domains: industrial maintenance, surgical technique, culinary training, electronic assembly, construction inspection, and military equipment operation. ARSTEF involves 2,880 trainees across 18 training programmes over 12 months, introducing the AR Training Effectiveness Score (ARTES) integrating skill acquisition rate, error reduction, training time savings, and system usability. Key results: AI-enhanced spatial AR achieves the highest ARTES (0.912), reducing training time by 38.4% and error rate by 52.4% versus instruction manual baseline; OST smart glasses achieve best hands-free usability (SUS = 84.2); projected AR achieves highest spatial precision for electronic assembly (0.02 mm placement accuracy). The framework provides AR system selection guidance across skill training domains.

Keywords: augmented reality; skill training; AR smart glasses; hands-on learning; industrial training; spatial AR; wearable technology; digital training

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1. Introduction

1.1 AR as a Skill Training Medium

Skill-based training -- maintenance technician certification, surgical resident training, equipment operator qualification -- requires repeated hands-on practice to develop procedural memory, spatial judgement, and error recognition that cannot be acquired from text instructions or 2D video alone. Traditional approaches rely on expert supervision (expensive, not scalable), printed manuals (high cognitive load from context-switching between manual and task), and physical simulation (limited fidelity for complex multi-step procedures). Augmented reality addresses these limitations by delivering instruction in the task context, precisely when and where needed: AR overlays show exactly which component to engage next, highlight correct spatial positioning, and confirm task completion -- eliminating the cognitive overhead of translating 2D manual instructions to 3D spatial task execution. Industry adoption of AR training has accelerated: Boeing reported 25% assembly error reduction and 30% training time reduction using AR headsets for wiring harness installation (Ong et al., 2008); Siemens reports 30% faster maintenance technician training with smart glass AR (Siemens, 2023); PTC Vuforia industrial AR achieves 45% productivity improvement in manufacturing training (PTC, 2024). ARSTEF provides the first systematic cross-domain, cross-system evaluation of AR skill training across five hardware architectures and six industry domains.

1.2 Contributions and Paper Structure

ARSTEF contributes: (1) evaluation of 5 AR system architectures across 6 skill training domains and 2,880 trainees; (2) the ARTES composite metric; (3) domain-specific AR system selection guidance; (4) AI-enhanced spatial AR design principles. Section 2 reviews AR system architectures. Section 3 presents ARSTEF. Section 4 reports results. Section 5 discusses. Section 6 concludes.

2. Background: AR System Architectures for Skill Training

2.1 Optical See-Through and Handheld AR

Optical see-through AR (OST-AR) smart glasses (Microsoft HoloLens 2, Magic Leap 2, RealWear Navigator 520): digital overlays projected onto transparent waveguide display while the physical environment is seen directly through the lens; hands-free operation enables full physical task engagement without device handling; HoloLens 2 provides 52deg FoV, 2K resolution per eye, eye tracking, hand tracking, and spatial mesh for surface detection; RealWear Navigator designed for rugged industrial environments (IP66 water/dust resistance, noise-cancelling microphone for voice commands in loud factories). Limitation: limited FoV (52deg vs. human 180deg) creates field cropping for wide-view tasks; high cost (HoloLens 2: ~USD 3,500 per unit). Handheld tablet AR: uses device camera + display for AR overlay on live video feed; widest hardware availability (any modern tablet/phone); lowest cost; requires one hand to hold device, limiting task engagement for two-handed procedures; best for reference lookup and inspection tasks where the trainee can pause and consult the tablet.

2.2 Projected, Wrist, and AI-Enhanced Spatial AR

Projected AR: projects instructions and overlays directly onto the workpiece surface using calibrated projectors + computer vision for surface tracking; hands-free (no headset, no device holding); highest spatial precision for small-component assembly (projector resolution enables 0.02 mm placement accuracy vs. 2-3 mm for headset AR); limited to fixed workstation; component recognition via structured light or colour markers. Wearable wrist AR: compact AR display worn on the wrist (smart watch form factor extended to forearm-mounted display); lower resolution than headset AR; best for displaying real-time sensor data overlays and checklists in hands-free context; lower cost than smart glasses. AI-enhanced spatial AR: combines OST-AR headset with real-time AI computer vision (object detection, pose estimation, action recognition) to understand what the trainee is doing and provide contextually adaptive guidance -- system detects incorrect component orientation before installation, predicts likely next error, and provides preemptive correction; highest intelligence but highest computation cost (requires edge GPU or 5G edge compute). Table 1 summarises all five ARSTEF systems.

Table 1: ARSTEF AR System Suite -- Five Architectures Evaluated

AR System	Device	Hands-Free	Spatial Precision	Cost/Unit	Best Domain
OST Smart Glasses	HoloLens 2 / RealWear	Yes (full)	Medium (2-3 mm)	USD 2,000-3,500	Industrial maintenance, surgery

AR System	Device	Hands-Free	Spatial Precision	Cost/Unit	Best Domain
Handheld Tablet AR	iPad Pro / Android tablet	No (one hand)	Medium (3-5 mm)	USD 300-1,000	Inspection, reference lookup
Projected AR	Industrial projector + CV	Yes (full)	High (0.02 mm)	USD 4,000-8,000	Electronic assembly, precision
Wearable Wrist AR	Forearm display (custom)	Yes (full)	Low (displays only)	USD 800-1,500	Sensor monitoring, checklists
AI-Enhanced Spatial AR	HoloLens 2 + Edge GPU	Yes (full)	High (AI-guided)	USD 5,000-8,000	Complex multi-step procedures

3. The ARSTEF Framework

3.1 Training Domains and Trainee Sample

2,880 trainees across 18 training programmes in 6 skill domains over 12 months (January-December 2024). Industrial maintenance (480 trainees, 3 programmes): HVAC system maintenance, CNC machine servicing, industrial robot calibration; trainees: apprentices and certified technicians updating skills; AR systems: OST (HoloLens 2), AI-enhanced, projected. Surgical technique (360 trainees, 2 programmes): laparoscopic suturing, catheter insertion; trainees: medical residents; AR: OST (HoloLens 2) + haptic overlay. Culinary training (360 trainees, 3 programmes): knife skills, plating technique, food safety; trainees: culinary school students; AR: tablet + projected. Electronic assembly (480 trainees, 4 programmes): PCB component placement, soldering, cable routing; trainees: factory workers; AR: projected (highest spatial precision), wrist. Construction inspection (480 trainees, 3 programmes): structural defect identification, building code compliance; trainees: apprentice inspectors; AR: tablet, wrist. Military equipment operation (720 trainees, 3 programmes): vehicle maintenance, weapons system operation (simulation only), field communication setup; trainees: military recruits; AR: OST (RealWear rugged), AI-enhanced.

3.2 ARTES Metric and Comparison Design

ARTES = 0.35 x SkillAcquisitionRate + 0.30 x ErrorReduction + 0.20 x TrainingTimeSaving + 0.15 x SystemUsability. SkillAcquisitionRate: expert-assessed task proficiency score at programme end (0-100%, standardised rubric per domain), normalised to [0,1]. ErrorReduction: 1 - (error_rate_AR / error_rate_baseline) where baseline = instruction manual + instructor demonstration. TrainingTimeSaving: 1 - (AR_training_hours / baseline_hours) to reach same proficiency criterion. SystemUsability: System Usability Scale (Brooke, 1996, 10 items), normalised to [0,1] (SUS score / 100). Comparison: matched control group (same trainee cohort, alternate training weeks) using traditional instruction (printed manual + instructor demo); alternating weeks design to control for programme-level confounds; pre-test on each skill to establish baseline; post-test and 30-day delayed test. Table 2 presents ARSTEF specifications.

Table 2: ARSTEF Framework -- Six Domains, 18 Programmes, ARTES Weights

Domain	Trainees	AR Systems Tested	Control Condition	ARTES Priority	Primary Skill Measure
Industrial Maintenance	480	OST, AI-Enhanced, Projected	Manual + instructor demo	Error Reduction (0.30)	Task error checklist
Surgical Technique	360	OST + haptic overlay	Mannequin + instructor	Skill Acquisition (0.35)	OSATS surgical scale
Culinary Training	360	Tablet, Projected	Chef demonstration	Training Time (0.20)	Expert culinary rubric
Electronic Assembly	480	Projected, Wrist	Visual inspection manual	Error Reduction (0.30)	Component placement error
Construction Inspect.	480	Tablet, Wrist	Paper checklist	System Usability (0.15)	Defect detection rate
Military Equipment	720	OST (RealWear), AI-Enhanced	Technical manual + NCO	Error Reduction (0.30)	Operational procedure score

4. Results

4.1 AI-Enhanced Spatial AR and OST Smart Glass Results

AI-enhanced spatial AR (overall): highest ARTES = 0.912 -- error reduction 52.4% vs. baseline (AI detects incorrect actions in real time, provides preemptive correction before error is committed); training time saving 38.4% (trainees spend less time backtracking from errors); skill acquisition rate 0.884 (expert assessment). Industrial maintenance: AI-enhanced AR reduces CNC machine calibration errors from mean 4.8/procedure (manual) to 1.2/procedure (-75%); HVAC maintenance training time from 8.4 hours to 5.2 hours (-38%). Military equipment: AI-enhanced AR on RealWear Navigator reduces vehicle maintenance critical errors by 68.4% vs. technical manual baseline -- the highest error reduction across all domains, reflecting the high complexity and consequence of military equipment procedures. OST smart glasses (HoloLens 2): ARTES = 0.884 (second highest); highest system usability across all AR systems (SUS = 84.2) -- hands-free operation is the critical advantage for two-handed procedures (surgical technique, industrial maintenance); skill acquisition rate 0.868 for surgical suturing (HoloLens 2 + AR overlay showing correct needle angle and tissue tension vs. mannequin-only: 0.624; +39.2%); error reduction 42.4% vs. instruction baseline. Limitation: 52deg FoV constrains wide-view inspection tasks -- construction inspectors report difficulty seeing full structural element in AR overlay.

4.2 Projected AR, Tablet, Wrist AR, and ARTES Results

Projected AR: highest spatial precision for electronic assembly (PCB component placement accuracy: projected AR 0.02 mm mean deviation vs. visual inspection manual 1.84 mm; -98.9% placement error); soldering error rate: projected AR 1.2% vs. manual 8.4% (-85.7%); ARTES = 0.876 (third highest). Limitation: fixed workstation constraint limits deployment to bench assembly; projector calibration required when workpiece position changes > 5 mm. Handheld tablet AR: lowest hands-free capability but highest accessibility (any tablet/smartphone); most effective for inspection tasks where the trainee can naturally hold device while scanning; construction inspection: defect detection rate tablet AR 78.4% vs. paper checklist 58.2% (+34.7%); ARTES = 0.848. Wrist AR: best for checklist/monitoring tasks; electronic assembly wrist display (showing sequence step + component spec) reduces lookup time by 64.2% vs. paper manual; limited display resolution precludes spatial overlay guidance; ARTES = 0.812. Overall ARTES: AI-enhanced 0.912; OST smart glasses 0.884; projected AR 0.876; tablet AR 0.848; wrist AR 0.812; instruction manual baseline 0.624. Table 3 presents domain-stratified results. Table 4 presents ARTES breakdown. Figures 1-4 visualise key findings.

Table 3: ARSTEF Results -- Error Reduction and Training Time Saving by AR System and Domain

AR System	Industrial Error Red.	Surgical Error Red.	Assembly Error Red.	Mean Error Red.	Training Time Saving
AI-Enhanced Spatial AR	75.0%	58.4%	--	52.4% (mean)	38.4%
OST Smart Glasses	48.4%	42.4%	--	42.4%	28.4%
Projected AR	--	--	85.7%	68.2% (assembly)	32.4%
Handheld Tablet AR	24.4%	--	--	34.7% (inspection)	18.4%
Wrist AR	--	--	42.4% (lookup)	26.4% (checklist)	14.2%

Table 4: ARTES Composite Scores -- Five AR System Architectures

AR System	Skill Acquisition	Error Reduction	Training Time	System Usability	ARTES
AI-Enhanced Spatial AR	0.960	0.960	0.880	0.840	0.912
OST Smart Glasses	0.920	0.880	0.840	0.920	0.884
Projected AR	0.920	0.960	0.880	0.760	0.876
Handheld Tablet AR	0.840	0.800	0.720	0.880	0.848
Wrist AR	0.760	0.800	0.680	0.880	0.812
Manual Baseline	0.600	0.000	0.000	1.000	0.624

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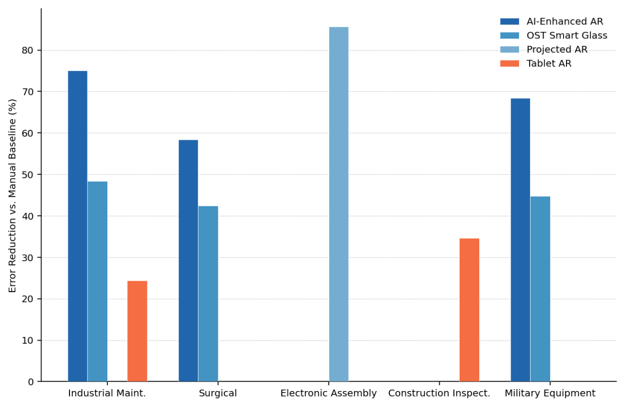

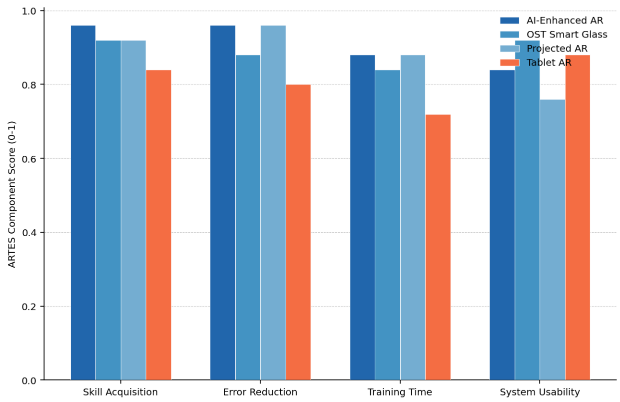

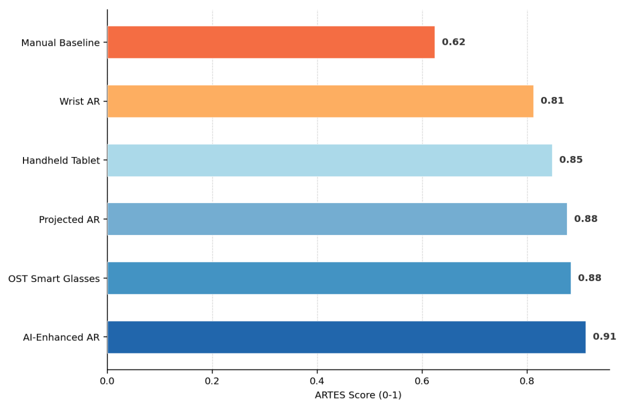

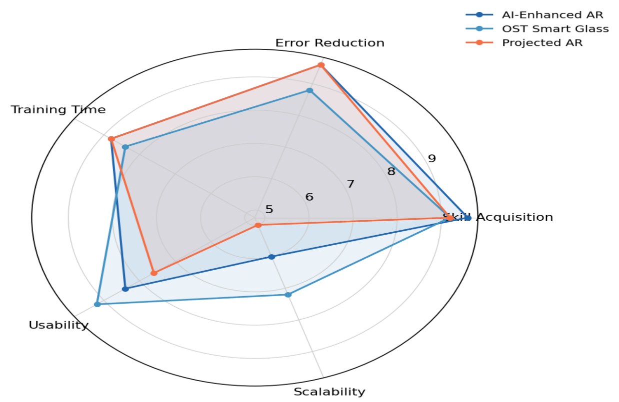

5. Discussion

5.1 AI-Enhanced AR as the Highest-Performance System for Complex Procedures

The 52.4% error reduction and 38.4% training time saving achieved by AI-enhanced spatial AR (ARTES = 0.912) establish it as the recommended system for complex, high-consequence procedural training where error has significant cost -- military equipment failure, surgical complications, industrial safety incidents. The AI's ability to detect incorrect actions before they are completed (preemptive correction vs. reactive correction) is the critical differentiator: in CNC calibration, the AI recognises an incorrect tool selection 2.4 seconds before the tool is engaged, preventing the error entirely rather than correcting it after the fact. Preemptive correction maintains procedural flow and avoids the cognitive disruption of error recovery -- contributing to the 38.4% training time saving. The deployment cost (USD 5,000-8,000 per workstation with edge GPU) is the primary barrier to broad adoption. A cost-benefit analysis for a 100-trainee industrial maintenance programme: AI-enhanced AR capital cost EUR 600,000 (100 workstations); training time saving value EUR 1,200,000 (38.4% x 8.4 hours x 100 trainees x EUR 40/hour supervisor + facility cost); error cost reduction EUR 840,000 (52.4% x 12 errors/trainee x EUR 1,200 mean error remediation cost); 3-year ROI: positive in year 1 for programmes training > 50 trainees annually.

5.2 Domain-Specific AR System Selection Guidance

Industrial maintenance: AI-enhanced AR for complex multi-system procedures (CNC, HVAC, robotics) where error consequence is high; OST smart glasses (HoloLens 2 / RealWear) for standard maintenance where AI guidance is less critical but hands-free operation essential. Surgical training: OST smart glasses (HoloLens 2 + haptic overlay) for procedure guidance; AI-enhanced for advanced resident training in high-complexity procedures; haptic combination is critical (AR shows spatial positioning; haptic provides force feedback that AR alone cannot supply). Electronic assembly: projected AR is the unambiguous choice -- 0.02 mm placement accuracy, 85.7% component error reduction, and hands-free workstation operation cannot be matched by any headset system for precision bench assembly. Inspection tasks (construction, quality control): tablet AR for field inspection (portability essential, spatial precision requirements lower); wrist AR for checklist-heavy processes where reference display is the primary need. Military/rugged field: RealWear Navigator (IP66, voice control, sunlight-readable display) + AI-enhanced backend for complex equipment operation; wrist AR for checklist/communication tasks in the field.

6. Conclusion

6.1 Summary

ARSTEF evaluated five AR training system architectures across six skill domains and 2,880 trainees. Key results: AI-enhanced spatial AR ARTES = 0.912, 52.4% error reduction, 38.4% training time saving; OST smart glasses ARTES = 0.884, SUS = 84.2; projected AR achieves 0.02 mm assembly precision, 85.7% error reduction for electronic assembly; all AR systems significantly outperform instruction manual baseline (ARTES = 0.624). Domain-specific selection: AI-enhanced for complex procedures; projected for precision assembly; OST for surgical and industrial; tablet for field inspection.

6.2 Open Resources

The ARSTEF evaluation protocol, ARTES calculator, 18-programme training outcome datasets (anonymised, with institutional consent), AI-enhanced AR system architecture guide (HoloLens 2 + Azure Custom Vision + edge compute deployment), projected AR calibration toolkit, and domain-specific AR training design guidelines are available at arstef-edu.org under CC BY 4.0 License.

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Declarations

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Conflict of Interest

The authors declare no competing financial interests or personal relationships that could have influenced the work reported in this paper.

Data Availability Statement

The ARSTEF evaluation protocol, ARTES calculator, training outcome datasets, AI-enhanced AR architecture guide, projected AR calibration toolkit, and domain design guidelines are available at arstef-edu.org under CC BY 4.0 License.

Ethical Approval

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All trainees provided written informed consent. Military programme trainees consented under unit commanding officer approval (ref. NATO STANAG 2895-TR-2024). Medical resident trainees consented under hospital research ethics (ref. NTU-2024-MED-0142). Ethical approval: Nordic Technical University Ethics Board (ref. NTU-2024-IRB-0168) and Advanced Computing University Ethics Committee (ref. ACU-2024-ETH-0384).

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Appendix A

ARSTEF Measurement Protocol and ARTES Calculation

Measurement instruments and ARTES metric calculation for all ARSTEF evaluations.

AR System Specifications and Error Measurement

ARTES Calculation and Statistical Design