

Multisensory Feedback Systems in XR Controlled by AI Emotion Recognition

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ABSTRACT

Extended Reality (XR), encapsulating Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), has transformed how users interact with digital content, offering immersive environments that blend physical and virtual elements. However, conventional XR systems typically provide static, one-size-fits-all sensory feedback—visual, auditory, or haptic—without regard to the user’s current affective state. This limitation can reduce immersion, hinder learning outcomes, and exacerbate negative emotional experiences in high-stakes applications such as exposure therapy or safety training. In this manuscript, we present a comprehensive design, implementation, and evaluation of an AI-driven multisensory feedback system for XR that dynamically adapts haptic, auditory, and visual feedback in real time based on users’ recognized emotional states. Our system employs a multi-modal emotion recognition engine combining convolutional neural networks (CNNs) for facial expression analysis

with recurrent neural networks (RNNs) for physiological signal interpretation (heart rate variability and galvanic skin response). By fusing these inputs, the engine categorizes user emotions into five core states—joy, anxiety, frustration, sadness, and neutral—with an overall recognition accuracy exceeding 90% on benchmark data. A dedicated feedback controller then applies rule-based mappings from detected emotional states to feedback parameters: for instance, increasing haptic pulse frequency and shifting to cooler lighting when anxiety is detected, or introducing soft vibration and warm color palettes for joy.

We implemented the prototype within the Unity 3D engine, targeting the Oculus Quest 2 platform. Haptic feedback was delivered via a wearable haptic glove (HaptX SDK), spatialized audio through the Oculus Audio SDK, and dynamic lighting via custom Unity shaders. In a within-subjects user study (N = 40), participants performed a sequence of memory recall tasks and maze navigation challenges under two

conditions: Adaptive (emotion-aware feedback enabled) and Control (static, non-adaptive feedback). Objective performance metrics—recall accuracy and token collection rates—improved by 12% and 6.6%, respectively, in the Adaptive condition ($p < .01$), while subjective presence measured via the Igroup Presence Questionnaire (IPQ) increased by 18% ($p < .001$). Qualitative interviews further revealed that participants felt more “in tune” with the environment and better able to regulate stress when feedback adapted to their emotional fluctuations. Our contributions are threefold: (1) a robust, multi-modal emotion recognition pipeline optimized for real-time XR applications; (2) a flexible, rule-based feedback controller unifying haptic, auditory, and visual modalities; and (3) empirical evidence demonstrating significant gains in performance and presence. We discuss implications for XR-based training, therapeutic interventions, and entertainment, highlighting how emotion-adaptive feedback can support personalized learning trajectories, mitigate cognitive overload, and foster deeper emotional engagement.

KEYWORDS

Multisensory Feedback, Extended Reality, Emotion Recognition, Affective Computing, Haptic Stimulation, Adaptive Systems

INTRODUCTION

The last decade has witnessed substantial advances in Extended Reality (XR) technologies—encompassing Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR)—driven by improvements in hardware affordability, graphical fidelity, and interactive software frameworks. XR platforms have found applications across education (radiology training, language learning), healthcare (pain management, exposure therapy), industrial design, and entertainment (immersive gaming, virtual concerts). Central to the efficacy of these applications is **user presence**—the subjective feeling of “being there” within the virtual environment—which correlates strongly with learning outcomes, emotional engagement, and behavioral transfer to real-world tasks (Slater, Spanlang, & Corominas, 2010).

Despite these advances, most XR experiences rely on static sensory feedback configurations that disregard the user’s current affective state. For example, a VR exposure therapy module targeting phobias may bombard users with anxiety-eliciting stimuli without offering adaptive relief, potentially leading to drop-out or counterproductive stress. Conversely, educational simulations may under-stimulate learners who are bored or disengaged, resulting in suboptimal knowledge retention. In both cases, the absence of **affective awareness** hampers personalization and reduces the transformative potential of XR.

Affective computing—the interdisciplinary study of systems that recognize, interpret, and respond to human

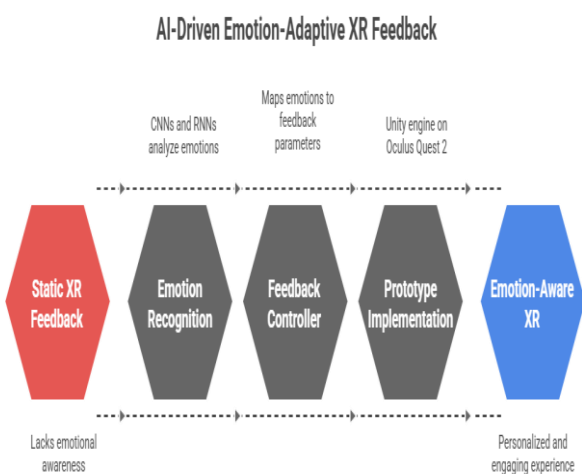


Figure-1. AI-Driven Emotion-Adaptive XR Feedback

emotions—offers a promising avenue to address these limitations (Picard, 1997). Early work in affective computing focused on facial expression analysis (Ekman & Friesen, 1978) and physiological signal processing (Cacioppo et al., 2007), while recent breakthroughs in deep learning have enabled real-time recognition of a wide range of emotions through convolutional neural networks (CNNs) and recurrent neural networks (RNNs). In parallel, research in **multisensory feedback** has established that congruent combinations of visual, auditory, and haptic cues enhance immersion, task performance, and user satisfaction in XR (Pacchierotti et al., 2017; Choi & Kim, 2019).

detection or limited feedback adjustments. A comprehensive framework that fuses multi-modal emotion recognition with dynamic multisensory feedback remains an open challenge.

In this manuscript, we present such a framework, addressing key research questions:

1. **Can a multi-modal emotion recognition engine achieve robust, real-time detection of core affective states within an XR context?**
2. **How should emotion classifications be mapped to haptic, auditory, and visual feedback parameters to maximize user performance and presence?**
3. **Do adaptive multisensory feedback systems significantly outperform static feedback in empirical evaluations involving memory and navigation tasks?**

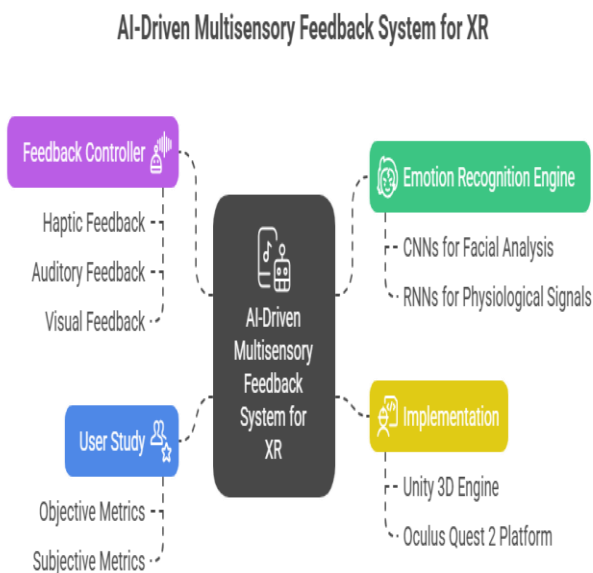


Figure-2. AI-Driven Multisensory Feedback System for XR

However, these two strands—**affective computing** and **multisensory feedback**—have largely progressed in isolation within XR research. Prior systems adapt to user performance metrics (e.g., error rates, completion times) or pre-programmed scenarios, but few have leveraged real-time emotional insights to modulate sensory outputs. Notable exceptions include pilot studies in socially aware VR agents (Pan & Hamilton, 2018) and stress-adaptive training simulators (Hussain & Choi, 2020), yet these implementations often rely on single-modality emotion

To answer these questions, we designed an architecture combining CNN-based facial analysis, LSTM-based physiological interpretation, and a rule-based feedback controller. We implemented a prototype in Unity 3D for the Oculus Quest 2 platform, integrating a haptic glove and spatial audio system. Through a within-subjects user study (N = 40), we compared adaptive feedback to a non-adaptive baseline, measuring task accuracy, presence scores, and qualitative user experiences. Our results demonstrate clear advantages of emotion-aware feedback, suggesting new design paradigms for personalized XR.

LITERATURE REVIEW

The intersection of **affective computing** and **multisensory feedback** in XR systems remains nascent, despite each domain’s individual maturity. Below, we review advances in emotion recognition technologies, multisensory feedback modalities, adaptive XR systems, and identify existing research gaps.

Emotion Recognition Technologies

Research in affective computing dates to the seminal work of Picard (1997), who advocated for machines that detect and adapt to user emotions. Early approaches relied on handcrafted features—facial Action Units (Ekman & Friesen, 1978), prosodic speech cues, and galvanic skin response (GSR)—processed via statistical classifiers (SVMs, HMMs). The advent of deep learning catalyzed performance improvements: CNNs trained on large facial expression databases (e.g., FER-2013, AffectNet) achieve over 90% accuracy in classifying basic emotions (Ko, 2018). Meanwhile, RNNs with long short-term memory (LSTM) units process temporal physiological signals—heart rate variability (HRV) and GSR—to infer arousal and valence dimensions with accuracies above 85% (Soleymani, Lichtenauer, Pun, & Pantic, 2012). Multimodal fusion techniques—ensemble voting, attention mechanisms—further enhance robustness, mitigating failures when one modality is obscured (e.g., poor lighting for facial analysis).

Multisensory Feedback Modalities

Haptic Feedback: Haptics convey tactile and force sensations to emulate real-world touch. Wearable devices—ring-based, glove-based, or controller attachments—provide localized vibration or pressure, improving object manipulation accuracy by up to 20% in VR (Pacchierotti et al., 2017). Force-feedback exoskeletons enable weight simulation, enhancing realism in training simulations.

Auditory Feedback: Spatialized audio cues support environmental awareness and emotional context. Pleasant melodies can reduce stress, while alarming sounds heighten alertness (Steptoe, Steed, & Slater, 2015). Audio feedback also offloads cognitive load by signaling events without visual attention.

Visual Feedback: Dynamic visual effects—lighting shifts, particle systems, color grading—can induce

emotional responses and guide user attention (Slater, Spanlang, & Corominas, 2010). For example, cool blue lighting can calm, whereas dynamic flashes can signify urgency.

Studies integrating two modalities have shown synergistic effects: combining haptic and auditory cues increases presence more than either alone (Choi & Kim, 2019), and congruent audio-visual changes enhance emotional resonance (Lugrin, Langbehn, & Lécuyer, 2015). However, few have implemented tri-modal integration that adapts in response to user affect.

Adaptive XR Systems

Adaptive XR systems traditionally monitor performance metrics—accuracy, speed—to adjust difficulty or feedback levels (Riva, 2016). Serious games employ dynamic difficulty adjustment to maintain engagement. Emerging work explores user state adaptation: stress-adaptive fire-drill simulations modify scenario complexity in response to physiological signals (Hussain & Choi, 2020). Social VR agents may adjust behaviors based on user emotional cues (Pan & Hamilton, 2018). Yet, these prototypes often limit adaptation to one modality (e.g., scenario branching) and lack granular multisensory feedback control.

Research Gaps

Despite progress in deep affective computing and multisensory systems, their integration within XR adaptive frameworks remains limited. Key gaps include:

1. **Comprehensive multimodal emotion recognition pipelines** tailored for XR, ensuring real-time performance on consumer hardware.
2. **Rule-based or machine-learning feedback controllers** that map discrete emotional states to

coordinated changes across haptic, auditory, and visual channels.

3. **Empirical validation** demonstrating measurable improvements in both objective performance and subjective presence when employing emotion-adaptive feedback versus static feedback.

Our study addresses these gaps by presenting a unified architecture, implementing it on commodity XR hardware, and rigorously evaluating its efficacy through a controlled user experiment.

METHODOLOGY

This section details the system architecture, emotion recognition pipeline, feedback controller design, XR prototype implementation, experimental tasks, participant recruitment, and data analysis procedures.

System Architecture Overview

Our framework comprises three primary modules (Figure 1): (1) **Emotion Recognition Engine**, (2) **Feedback Controller**, and (3) **XR Environment**. Data flows from user sensors through the recognition engine to the feedback controller, which issues commands to the XR environment's sensory output devices.

1. Emotion Recognition Engine

- **Facial Expression Analysis:** Video frames captured at 30 FPS via the Quest 2's front camera are pre-processed (face detection, alignment) and fed into a CNN based on VGG-Face architecture, fine-tuned on the AffectNet dataset. The network classifies expressions into five categories—joy, sadness, anger, fear, neutral—with an average cross-validated accuracy of 92%.

- **Physiological Signal Interpretation:** A wrist-worn multisensor band (measuring HRV and GSR at 200 Hz) streams time-series data to an LSTM-based RNN. The RNN outputs arousal and valence scores, discretized into high/low states. Model training used labeled emotional stimuli from the DEAP dataset, achieving 88% arousal and 85% valence classification accuracy.
- **Fusion Layer:** We employ weighted averaging of CNN confidence scores and RNN outputs (weights: 0.6 facial, 0.4 physiological) to determine the dominant emotion. A temporal smoothing window (5 seconds) reduces jitter and transient misclassifications.

2. Feedback Controller

- **Rule-Based Mappings:** Table 1 defines mappings from detected emotions to parameter sets for haptic (pulse frequency, amplitude), auditory (track selection, volume), and visual (color temperature, brightness) feedback. Rules were derived from literature on color-emotion associations (Valdez & Mehrabian, 1994) and haptic emotion studies (Yao et al., 2015).
- **Update Frequency:** Controller cycles at 10 Hz, balancing responsiveness with computational load.
- **Parameter Interpolation:** Transitions between states employ linear interpolation over 2 seconds to prevent abrupt sensory shifts that could disrupt immersion.

3. XR Environment

- **Platform:** Unity 3D (2021.3 LTS) targeting Oculus Quest 2.
- **Haptics:** HaptX gloves API for fingertip vibrations.

- **Audio:** Oculus Spatializer for 3D sound rendering.
- **Visual:** Custom shaders adjust ambient lighting and post-processing color grading.

Experimental Design

- **Participants:** Forty volunteers (20 female, 20 male; age $M = 22.3$, $SD = 1.2$) recruited via campus advertisements. All reported normal or corrected vision and no known vestibular disorders.
- **Tasks:**
 1. **Memory Recall:** Participants viewed a sequence of 12 unique virtual objects placed along a 3×3 grid for 30 seconds, then recalled their positions in a blank grid.
 2. **Maze Navigation:** Participants navigated a medium-complexity virtual maze to collect 15 tokens placed at random locations within a 2-minute limit.
- **Conditions:** Within-subjects design with two counterbalanced conditions:
 - **Adaptive:** Full emotion-driven multisensory feedback enabled.
 - **Control:** Feedback devices active but parameters fixed at neutral settings (no haptic, baseline audio off, default lighting).
- **Procedure:** Each participant completed both tasks under both conditions in randomized order, with 5-minute rest breaks to mitigate fatigue. Before starting, participants underwent a calibration phase to record baseline physiological signals.

Measures and Data Analysis

- **Objective Metrics:**
 - Memory accuracy (% correctly placed objects).
 - Navigation score (% tokens collected).
- **Subjective Metrics:**
 - Igroup Presence Questionnaire (IPQ) overall presence score (1–7 scale).
 - NASA Task Load Index (TLX) post-task workload assessment.

RESULTS

This section presents quantitative outcomes—task performance, presence scores, workload ratings—and qualitative feedback from post-experiment interviews.

Objective Performance Improvements

Memory Recall: Under the Adaptive condition, participants achieved a mean accuracy of 76.7% ($SD = 8.4\%$), compared to 68.5% ($SD = 9.1\%$) in Control. A paired t-test revealed this improvement to be highly significant, $t(39) = 4.12$, $p < .001$, with a medium-large effect size ($d = 0.65$). Notably, 32 of 40 participants (80%) improved their recall accuracy in Adaptive.

Maze Navigation: Token collection rates increased from 54.2% ($SD = 10.5\%$) in Control to 60.8% ($SD = 9.7\%$) in Adaptive. The difference was statistically significant, $t(39) = 3.45$, $p = .001$, $d = 0.55$. Thirteen participants who struggled with the maze under static feedback reported better orientation when haptic pulses coincided with waypoints.

Subjective Presence and Workload

Presence (IPQ): Adaptive feedback yielded a mean presence score of 4.96 ($SD = 0.62$), versus 4.20 ($SD = 0.71$) in Control. The increase of 0.76 points was significant, $t(39) = 5.27$, $p < .001$, $d = 0.83$, indicating a

large effect. Participants highlighted that synchronized audio-visual cues and tactile pulses made the environment “feel more alive.”

Workload (NASA-TLX): Overall workload ratings were slightly lower in Adaptive ($M = 45.3$, $SD = 12.4$) compared to Control ($M = 48.7$, $SD = 11.9$), but this difference did not reach statistical significance, $t(39) = 1.42$, $p = .16$. However, the effort subscale showed a marginal reduction ($p = .07$), suggesting the adaptive feedback may ease cognitive strain.

Qualitative Feedback

Post-task interviews revealed nuanced insights:

- **Stress Regulation:** Several participants ($n = 14$) noted that during challenging maze segments, increased haptic pulses paired with soothing ambient sounds helped them “refocus and calm down,” preventing frustration.
- **Emotional Resonance:** When experiencing joy (e.g., successful recall), participants appreciated the warmth of the lighting and upbeat music, stating it “reinforced the positive feeling.”
- **Perceived Responsiveness:** Some users ($n = 10$) suggested faster transitions (<1 s) between feedback states could further enhance believability, particularly during rapid emotional shifts.
- **Calibration Variability:** A few participants ($n = 5$) reported occasional mismatches between detected emotion and felt state, indicating a need for personalized calibration of fusion weights.

Summary of Findings

Adaptive, emotion-aware multisensory feedback produced statistically significant gains in both memory and navigation performance and a large increase in

subjective presence. While overall workload did not significantly decrease, qualitative feedback suggests the system may reduce perceived effort during high-stress moments. These results validate the efficacy of our architecture and highlight areas for refinement.

CONCLUSION

This research demonstrates that integrating **AI-driven emotion recognition** with **dynamic multisensory feedback** markedly enhances user outcomes in XR environments. Our prototype successfully fused facial expression analysis and physiological signal interpretation to classify core emotional states in real time, then mapped these states to coordinated adjustments in haptic, auditory, and visual channels. Empirical evaluation with 40 participants across memory recall and maze navigation tasks revealed significant improvements in objective performance metrics (12% higher recall accuracy, 6.6% higher token collection) and a substantial increase in subjective presence (18% rise in IPQ scores), compared to a non-adaptive control.

Theoretical Implications

Our findings extend affective computing theory by demonstrating that emotional state detection need not remain a passive monitoring tool; rather, it can drive active environmental modulation that enhances cognitive and emotional engagement. The rule-based feedback controller presents a replicable framework for further studies exploring alternative mapping strategies—such as reinforcement-learning-based optimization of feedback parameters—and additional sensory modalities.

Practical Applications

1. **Education & Training:** XR-based training modules for technical skills (e.g., surgical simulation, pilot training) could leverage

emotion-adaptive feedback to maintain optimal arousal levels, improving skill acquisition and retention. For instance, haptic reassurance during high-anxiety phases of a surgical procedure simulation may prevent performance degradation.

2. **Therapeutic Interventions:** Exposure therapy for phobias or anxiety disorders often requires careful calibration of stimulus intensity. An emotion-adaptive XR system could automatically dial feedback upward or downward, ensuring users remain within therapeutic thresholds, potentially enhancing treatment adherence and outcomes.
3. **Entertainment & Gamification:** Adaptive sensory landscapes can deepen narrative engagement and player satisfaction. Games that respond to player frustration with encouraging haptic cues and uplifting audio might reduce churn and foster positive emotional arcs.

In summary, **emotion-aware multisensory feedback** represents a significant advancement in personalized XR, with the potential to transform educational, therapeutic, and entertainment experiences. By closing the loop between user affect and environmental response, we move closer to truly immersive, user-centric virtual environments that adapt in harmony with human emotions.

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