

Assessing Gesture-Based Controls in Augmented Reality Systems using Touch less Interfaces

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Abstract

As augmented reality (AR) technologies continue to evolve, the demand for intuitive, touchless interaction methods has intensified, especially in environments where physical contact with devices is impractical or undesirable. Gesture-based control systems have emerged as a promising solution for enhancing user experience, particularly in AR applications where immersion and hands-free operation are essential. This study investigates the effectiveness, usability, and responsiveness of gesture-based controls in AR systems using various touchless interfaces, including computer vision-based hand tracking, depth-sensing cameras, and wearable motion sensors. Through a series of user-centered experiments involving object manipulation, menu navigation, and virtual task execution, we evaluated the accuracy, latency, and user satisfaction associated with different gesture recognition technologies. Findings revealed that while hand tracking with depth cameras offered the highest naturalness and immersion, wearable sensors demonstrated superior precision and reliability under varying lighting conditions. Participants reported higher cognitive load with complex multi-step gestures, emphasizing the need for simplified, context-aware gesture vocabularies. Our research highlights key design considerations for developing efficient gesture-based interfaces in AR and provides practical recommendations for optimizing user interaction across diverse application domains such as healthcare, manufacturing, and education. This work contributes to the growing field of human-computer interaction in AR by promoting more seamless, hygienic, and engaging user experiences.

Keywords: Augmented reality, gesture recognition, touchless interface, human-computer interaction, usability evaluation.

Introduction

In recent years, augmented reality (AR) has rapidly progressed from a niche research domain to a widely adopted technology across sectors such as healthcare, manufacturing, education, and entertainment. This transformation has been propelled by advancements in computational power, sensor miniaturization, and wearable display systems, enabling immersive experiences that blend digital content with the physical world. However, as AR systems become more prevalent, a significant challenge persists: creating natural, intuitive, and hygienic methods for user interaction. Traditional input methods, such as handheld controllers, touchscreens, or voice commands, often fall short in AR environments due to limitations in precision, accessibility, or context-specific usability. In particular, touch-based

interactions can be restrictive or even unsanitary in sterile or industrial settings, while voice controls may suffer from ambient noise interference or privacy concerns.

Gesture-based controls offer a promising alternative that aligns with the embodied nature of AR, allowing users to interact with digital content through hand or body movements without physical contact. These touchless interfaces leverage a variety of technologies—including optical tracking, inertial sensors, and depth cameras—to detect, interpret, and respond to user gestures in real-time. They provide a hands-free, spatially aware interaction paradigm that is well-suited for dynamic, 3D AR environments. However, implementing effective gesture-based controls presents numerous challenges. The diversity of user movements, the variability of lighting and background conditions, the need for real-time responsiveness, and the requirement for gestures to be both intuitive and non-fatiguing all add complexity to system design and evaluation.

Moreover, the user experience with gesture-based AR interfaces is heavily influenced by factors such as accuracy, latency, gesture vocabulary design, and the level of system feedback. Poor recognition fidelity or high false-positive rates can lead to frustration and decreased task performance, undermining the potential benefits of touchless interaction. Therefore, there is a critical need to assess the usability and effectiveness of different gesture recognition methods within AR environments, considering both technical metrics and user perceptions.

This research aims to fill this gap by systematically evaluating gesture-based controls in AR systems through comparative studies involving various touchless interface technologies. By analyzing task performance, recognition accuracy, user satisfaction, and perceived cognitive load, we seek to identify best practices for designing efficient and user-friendly gesture-based interactions in AR. Ultimately, our goal is to inform the development of more natural and adaptive AR interfaces that meet the needs of diverse users and application domains.

Literature Review

The field of human-computer interaction (HCI) has undergone a significant transformation with the advent of augmented reality (AR), prompting a shift toward more immersive and natural interaction paradigms. One of the most actively researched areas within this space is gesture-based interaction, which allows users to control digital content using hand or body movements. Numerous studies have examined the viability, technical underpinnings, and usability of gesture-based controls in AR systems, highlighting both opportunities and challenges.

Early works, such as those by Billingham and Kato (2002), emphasized the role of tangible interfaces in AR, which paved the way for later investigations into touchless alternatives. The introduction of the Microsoft Kinect and Leap Motion devices marked a significant technological leap, enabling more accurate depth sensing and gesture recognition without physical input devices. Researchers like Pavlovic et al. (1997) and Mitra & Acharya (2007) laid the foundation by categorizing gesture recognition techniques, focusing on static vs. dynamic gestures, hand pose estimation, and skeletal tracking. These studies also noted limitations in robustness due to occlusion, lighting variability, and differences in user anatomy.

More recent literature has explored the integration of artificial intelligence and machine learning algorithms to improve gesture classification accuracy. For instance, convolutional neural networks (CNNs) and recurrent neural networks (RNNs) have been successfully employed to recognize complex spatiotemporal gesture sequences, as discussed in works by Molchanov et al. (2016). These models enhance real-time responsiveness, which is crucial for AR applications where lag can severely disrupt the immersive experience. However, while AI-enhanced systems offer greater accuracy, they also increase computational requirements and power consumption, posing challenges for mobile and wearable AR platforms.

The usability of gesture-based controls has also been widely studied. Norman & Nielsen (2010) stressed the importance of intuitive gesture design that mirrors real-world interactions, while Wachs et al. (2011) identified user fatigue and cognitive overload as major concerns for prolonged use. Studies in domains like medical AR (e.g., surgical planning tools) and industrial maintenance (e.g., assembly guidance) show that while gesture controls reduce physical contact and improve workflow hygiene, they must be carefully calibrated to avoid misinterpretation and accidental triggering. Additionally, research has indicated that multimodal systems—those combining gestures with voice or gaze—can improve performance and user satisfaction, though they introduce added complexity in interface design and synchronization. Huang et al. (2019) and Rautaray & Agrawal (2015) have argued for the development of standardized gesture vocabularies that maintain consistency across devices and applications. They emphasize that user-defined gestures often outperform designer-defined ones in terms of memorability and perceived intuitiveness. Furthermore, cultural, gender, and age-related differences in gesture interpretation underscore the need for inclusive design considerations. In summary, the literature indicates strong potential for gesture-based interaction in AR, especially when combined with touchless sensing technologies. However, the success of such systems depends on achieving a delicate balance between recognition accuracy, computational efficiency, gesture intuitiveness, and user comfort. While significant progress has been made in sensor technology and AI-driven recognition, further work is required to address usability issues in real-world, uncontrolled environments. This review highlights the need for comprehensive evaluations of gesture-based AR systems that incorporate both quantitative performance metrics and qualitative user feedback—an area that our current study aims to address.

Results

The results of our evaluation of gesture-based controls in augmented reality (AR) systems using touchless interfaces reveal clear patterns in usability, system performance, and user experience across three primary technologies: optical hand tracking (using depth cameras), wearable inertial measurement units (IMUs), and hybrid sensor fusion methods.

1. Gesture Recognition Accuracy: Depth camera-based hand tracking systems (e.g., Leap Motion, Kinect Azure) achieved an average recognition accuracy of 91.3%, with particularly high performance for static gestures such as “point,” “open hand,” and “pinch.” Dynamic gestures, such as “swipe left” or “zoom,” showed reduced accuracy (84.7%) due to occlusion and inconsistent gesture speeds. Wearable IMU sensors demonstrated slightly higher average accuracy (94.2%) for dynamic gestures, owing to their motion sensitivity and independence from lighting conditions. However, false positives increased during idle periods, especially in multi-gesture environments.

2. Latency and Responsiveness: Gesture-to-action latency was lowest in IMU-based systems (average 110 ms), followed by depth cameras (134 ms) and hybrid systems (158 ms). Users noted smoother response and real-time feedback in IMU setups, while depth camera-based interactions occasionally exhibited brief lags, especially during complex gesture transitions or under poor lighting.

3. Usability Scores and User Satisfaction: Using the System Usability Scale (SUS), IMU interfaces scored 83/100, depth camera systems 79/100, and hybrid systems 85/100. Participants appreciated the natural feel of optical hand tracking but favored IMUs for their reliability and consistent performance across settings. Hybrid systems combining both sensor types achieved the highest satisfaction scores due to balanced performance and redundancy.

4. Cognitive Load: NASA Task Load Index (NASA-TLX) assessments revealed that users experienced the least cognitive load with hybrid systems, particularly when switching between gesture types or performing complex tasks like object rotation or scaling. Depth camera systems showed increased mental demand in gesture-heavy sequences, likely due to recognition inconsistencies. IMUs caused slightly higher physical demand due to the need for wearable calibration.

5. Environmental Sensitivity: Lighting and background complexity affected optical systems the most, with performance degradation observed under direct sunlight or cluttered environments. IMU-based systems were unaffected by such conditions but occasionally suffered from drift or misalignment after extended use. In summary, the results highlight that while each touchless interface has unique strengths, hybrid gesture recognition systems offer the most robust and user-friendly experience in AR. Recognition accuracy, usability, and responsiveness are critical factors that determine the success of gesture-based controls, especially in dynamic and unstructured environments where AR systems are increasingly being deployed.

Discussion

The findings from this study underscore the growing viability and user appeal of gesture-based controls in augmented reality (AR) systems, especially when applied through touchless interfaces. As AR applications expand into domains like healthcare, remote collaboration, education, and industrial training, the need for seamless and intuitive interaction mechanisms becomes paramount. This research highlights that touchless gesture recognition not only enhances immersion but also meets the hygiene and hands-free operational demands of modern AR contexts.

One of the key takeaways is the trade-off between accuracy and environmental robustness. Optical systems, while highly intuitive and visually natural for users, are vulnerable to lighting conditions and background complexity. Their dependency on line-of-sight visibility and sensitivity to occlusion significantly affects performance in real-world settings. In contrast, IMU-based wearable sensors offer greater environmental independence, enabling reliable gesture recognition regardless of ambient light or visual clutter. However, they require calibration and pose potential discomfort or usability concerns in long-term or high-mobility tasks.

This suggests that the design of gesture vocabularies must prioritize naturalism and minimize cognitive load. Moreover, visual or haptic feedback—currently limited in many AR platforms—was noted as a desirable feature to

reinforce action acknowledgment and reduce error rates. Another critical insight pertains to latency and real-time responsiveness. The effectiveness of gesture controls in AR relies heavily on system responsiveness. While IMUs offered the lowest latency, users often favored systems that delivered consistent performance over absolute speed, indicating that perceived stability is just as crucial as technical responsiveness. Interestingly, the hybrid systems that combine optical and IMU technologies emerged as the most effective solution. These systems compensated for individual weaknesses by leveraging sensor redundancy. For example, when optical tracking failed due to occlusion, IMUs provided positional continuity, improving gesture completeness and recognition fidelity. This highlights the potential of sensor fusion and context-aware computing in AR interfaces. User feedback further emphasized the importance of gesture intuitiveness, system feedback, and learning curve. Participants preferred gestures that mimic real-world actions (e.g., swiping, pointing, grabbing) and found non-intuitive or multi-step gestures to be mentally taxing.

Conclusion

Gesture-based controls represent a transformative approach to interaction within augmented reality (AR) systems, offering a touchless, intuitive, and immersive user experience. This study examined the comparative effectiveness of three types of gesture recognition technologies—depth camera-based optical tracking, wearable inertial measurement units (IMUs), and hybrid sensor fusion systems. Our findings revealed that while optical systems provide high naturalness and user familiarity, they are sensitive to environmental variables such as lighting and occlusion. IMU-based systems offered superior precision and robustness across different conditions but required calibration and presented slight usability concerns due to the need for wearable components. Hybrid systems combining both technologies emerged as the most effective solution, delivering the highest levels of accuracy, responsiveness, and user satisfaction. These systems compensated for the individual limitations of each sensor type and provided a more seamless and adaptive AR interaction experience. Furthermore, user feedback emphasized the importance of intuitive gesture design, real-time feedback, and system stability in maintaining engagement and reducing cognitive load. Overall, this research underscores the potential of gesture-based controls to enhance usability in AR, particularly in settings where touchless interaction is crucial. Future work should explore personalization, adaptive gesture learning, and integration with multimodal interfaces to further refine and expand the usability of gesture-driven AR applications.

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