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Factors Influencing the Formation of Augmented Reality Systems

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Conflicts of interest

The authors declare that there is no conflict of interest.

Abstract. This study identifies and analyzes the factors influencing the formation, functioning, usability, and efficiency of augmented reality (AR) systems. The first group of factors is determined by the technical characteristics of the system and the information infrastructure. The quality of the sensors determines the degree of detail and reliability of the initial data; devices with low accuracy can cause delays, drift, or jitter, which negatively affect the stability of the virtual object. Accurate positioning and tracking depend on GPS signals, visual-inertial odometry, or marker-based systems that can be affected by multichannel interference, signal jamming, or sensor noise, resulting in a mismatch between the physical and virtual worlds. Network bandwidth limitations affect real-time data streaming, cloud rendering, and multi-user synchronization, and unreliable connections result in skips or delays. The second group of factors refers to environmental conditions. Fluctuations in lighting can cause noise, decrease contrast, and disrupt object detection algorithms, which require the use of reliable computer vision techniques. This study proposes a solution to problems that improves the quality of augmented reality content and is key to the creation and development of AR systems.

Keywords: hardware and software, sensor fusion, environmental conditions, computer vision, real-time data

Authors' contribution

Kruglova L.V. — planning and overall supervision, validation; *Ceesay F.K.* — writing, visualization; *Samb R.* — conducting research. All authors read and approved the final version of the article.

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Факторы, влияющие на формирование систем дополненной реальности

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Аннотация. Определены и проанализированы факторы, влияющие на формирование, функционирование, удобство использования и эффективность систем дополненной реальности (ДР). Первая группа факторов обусловлена техническими характеристиками системы и информационной инфра-

Заявление о конфликте интересов

Авторы заявляют об отсутствии конфликта интересов.

структуры. Качество сенсоров определяет степень детализации и надежность исходных данных; устройства с низкой точностью могут вызывать задержку, дрейф или дрожание, что отрицательно влияет на стабильность виртуального объекта. Точное позиционирование и отслеживание зависят от сигналов GPS, визуально-инерциальной одометрии или систем на основе маркеров, которые могут подвергаться помехам от многоканальности, перекрытий сигналов или шума датчиков, что приводит к несоответствию между физическим и виртуальным мирами. Ограничения пропускной способности сети влияют на потоковую передачу данных в реальном времени, облачный рендеринг и многопользовательскую синхронизацию, а ненадежные соединения приводят к пропуску кадров или задержке. Ко второй группе факторов относятся условия окружающей среды. Колебания освещенности могут привести к появлению шума, снижению контрастности и нарушению алгоритмов обнаружения объектов, что требует применения надежных методов компьютерного зрения. Предложено решение задач, повышающее качество контента дополненной реальности и имеющее ключевое значение для создания и развития систем ДР.

Ключевые слова: аппаратно-программные средства, объединение датчиков, условия окружающей среды, компьютерное зрение, данные в реальном времени

Вклад авторов

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Introduction

In the rapidly advancing field of augmented reality (AR), the seamless integration of virtual elements into the physical world relies on more than just sophisticated software; it is also governed by a range of different factors. These factors affect every stage of AR model formation, from data capture and processing to rendering and user interaction, ultimately determining the system's accuracy, responsiveness, and overall user experience [1; 2].

Sensor quality and calibration are the backbone of reliable data acquisition. High-resolution cameras, wide dynamic-range sensors, and precise inertial measurement units (IMUs) deliver detailed visual and motion data, whereas low-fidelity devices can introduce latency, drift, and jitter. Regular calibration and sensor fusion techniques are essential for minimizing these errors and maintaining stable virtual overlays [3; 4].

Positioning and tracking accuracy depend on technologies such as GPS, visual-inertial odometry, and marker-based systems, all of which are susceptible to environmental interferences, such as multipath signal reflections, occlusions, and sensor noise. Ensuring precise alignment between the real and virtual worlds requires continuous refinement of Simultaneous Localization and Mapping (SLAM) algorithms and redundancy in tracking methods [5; 6].

Network performance is another critical factor, especially for cloud-assisted AR and multi-user experiences. Bandwidth limitations and latency can cause frame drops, synchronization issues, and delayed rendering, thereby undermining immersion. Leveraging edge computing and efficient data compression strategies help alleviate these network constraints and enable low-latency, high-fidelity AR interactions [7].

Furthermore, the complexity of physical environments, which are characterized by reflective surfaces, dynamic objects, and clutter, poses significant challenges for scene understanding and object recognition. Advanced environment-aware algorithms that adapt to changing conditions are necessary to maintain accurate and stable virtual content placement [8].

This study explores the key factors shaping the formation of AR systems, including technological advancements and environmental conditions [9].

1. Methods

1.1. Technological Advancements

Technological advancements are perhaps the most critical factor influencing AR (Figure 1). The evolution of hardware and software has dramatically enhanced AR capabilities. High-performance mobile devices, such as smartphones and tablets, have made AR accessible to a wider audience. The integration of advanced sensors (e.g., accelerometers, gyroscopes, and depth sensors) allows for more accurate tracking and interaction with the physical environment.

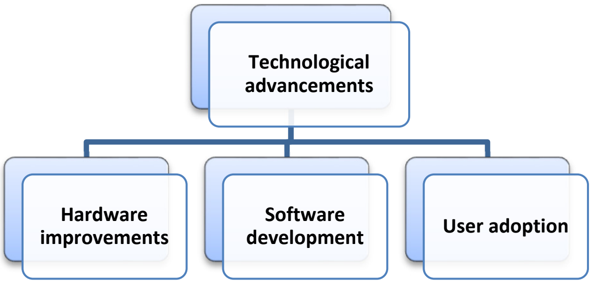

Figure 1. Technological advancements
Source: by F.K. Ceesay.

Moreover, dedicated AR hardware, such as smart glasses and head-mounted displays (HMDs), has further enriched user experiences. Devices such as Microsoft HoloLens and Magic Leap One enable hands-free interaction, making AR applications more practical in fields such as healthcare, education, and manufacturing.

On the software side, innovations in computer vision and machine learning have improved object recognition and tracking, which are essential for creating realistic AR experiences. Development platforms such as ARKit (Apple) and ARCore (Google) have simplified the creation of AR applications, fostering innovation and lowering barriers for developers [10; 11].

User adoption of AR applications affects user attention and behavior [12].

1.1.1. Hardware Improvements

Hardware improvements are key to advancing AR model formation, as they directly affect data quality, processing speed, user comfort, and overall system robustness. Major areas of enhancement include [13]:

Sensor Upgrades. Higher-resolution cameras and global-shutter imagers reduce motion blur and capture finer scene details, thereby improving feature detection.

Wide dynamic range (WDR) and High dynamic range (HDR) sensors handle extreme lighting contrasts (sunlit exteriors vs. dim interiors) more reliably.

Integrated depth sensors (time-of-flight, structured light, or LiDAR) provide real-time 3D geometry, boosting SLAM accuracy in feature-poor or textureless environments.

Miniaturized, low-noise IMUs (accelerometers, gyroscopes, and magnetometers) with on-chip temperature compensation reduce drift and jitter in motion tracking.

Display and Optics. Next-generation waveguide optics (diffractive or holographic) and pancake lenses enable slimmer and lighter AR glasses with wider fields of view (FOV) and improved brightness uniformity.

Micro-LED and OLED microdisplays offer higher pixel density, better contrast ratios, and lower latency than conventional LCDs, leading to sharper and more stable virtual overlays [14].

Adaptive focus and varifocal modules reduce eye strain by dynamically adjusting the focal distances to match the virtual content depth [15].

Compute and Power. Dedicated vision and AI accelerators (NPUs, VPUs) on edge devices accelerate neural network inference for object recognition, semantic segmentation, and visual-inertial odometry, reducing the reliance on cloud processing.

Heterogeneous multicore Systems on a Chip (SoCs) combine CPUs, GPUs, DSPs, and NPUs to balance real-time rendering, physics simulation, and computer vision tasks efficiently.

Advanced power-management Integrated Circuits (ICs) and high-capacity, fast-charging batteries extend the operation time without compromising temperature control. Improved thermal designs (vapor chambers and graphite shields) maintain performance under sustained loads.

Connectivity. Integrated 5G/6G modems with multi-gigabit throughput and ultra-low latency support cloud-assisted AR, large-scale multiplayer synchronization, and the remote streaming of complex 3D assets.

Wi-Fi 6/6E and Bluetooth LE Audio modules enable robust, low-latency local networking for device clusters, peripherals, and audio/video offload.

Form Factor and Ergonomics. The use of lightweight composite materials (carbon fiber and magnesium alloys) and balanced weight distribution reduce user fatigue, allowing longer sessions.

Modular hardware architectures allow developers to swap sensors, batteries, or compute modules to suit specific use cases, from industrial inspections to medical training [16].

Improved user interfaces (eye tracking, hand tracking, and voice control) offload mechanical controls, streamlining interactions and reducing accessory bulk [17].

Advancements across these hardware domains, including the integration of high-fidelity sensors, advanced display technologies, dedicated accelerators, next-generation connectivity, and ergonomic design, enable AR systems to achieve more accurate environment mapping, faster and more reliable rendering, and a substantially improved user experience.

1.1.2. Software Development

In modern software development for AR, a developer must integrate multiple subsystems, including real-time rendering, sensor processing, networking, and user interaction, into a cohesive, high-performance application [18]. The key considerations and best practices are as follows:

- Modular System Architecture. Layers such as rendering, sensor fusion, user interfaces (UI), and networking are isolated into distinct modules or services.

Modern AR systems are configured using a plugin-based design, in which components (e.g., tracking engines) can be swapped out without rewriting the core logic.

- Choice of Engines and SDKs:

Cross-platform frameworks: Unity and Unreal Engine offer extensive AR toolkits (AR Foundation, ARCore, and ARKit) for mobile and headset targets.

Native SDKs: when performance is critical, services can tap directly into ARKit (iOS) or ARCore (Android) APIs, bypassing engine overhead.

- Sensor Fusion and Real-Time Data Handling:

Time synchronization: Linear interpolation or hard-ware triggers can be used to align IMU, camera, and depth sensor timestamps.

Filtering: Extended Kalman filters (EKF) or complementary filters are employed to merge noisy streams and minimize drift.

- Advanced Computer Vision Pipelines:

Feature extraction: The combination of classical algorithms (ORB, FAST) with lightweight neural networks (MobileNet-based) provides robust detection under varied conditions.

Semantic understanding: Using on-device inferencing to recognize objects and surfaces enables context-aware interactions.

- Graphics and Rendering Optimizations:

Level-of-Detail (LOD): Dynamically adjusting mesh complexity based on distance and screen size maintains 60–90 FPS on mobile GPUs.

GPU instancing and batching: Reducing draw calls by grouping identical objects and materials enables to leverage compute shaders for offloading physics or lighting tasks.

- Networking and Distributed Experiences:

Low-latency protocols: UDP-based transports (e.g., WebRTC and QUIC) with forward-error correction can be used for real-time multi-user synchronization.

State reconciliation: The implementation of client-side prediction and server-authoritative state snapshots helps to hide interpolation delays.

- Continuous Integration / Continuous Deployment (CI/CD):

Automated testing: Device farms or emulators to run unit, integration, and performance tests should be created for every commit.

Build automation: Script builds for iOS, Android, and XR headsets, packaging assets, and running acceptance tests should be fulfilled before release.

- User Experience (UX), Accessibility, and Safety:

User comfort: Monitoring and reducing latency (motion-to-photon < 20 ms) and frame drops can be useful to prevent motion sickness [19].

Natural inputs: Fallback controls (touch, gamepad) when gesture or eye-tracking fails, and interfaces should meet accessibility guidelines.

- Security, Privacy, and Compliance:

Data encryption: Sensor streams and user metadata in transit (TLS) and at rest (AES) should be protected from hacking.

Consent and anonymity: The implementation of opt-in mechanisms and anonymized spatial maps should adhere to GDPR/CCPA.

- Debugging and Profiling:

Real-time dashboards: Telemetry (frame time, memory usage, and sensor latency) should be exposed in-app or via remote logging.

Offline analysis: Sensor streams and render logs should be recorded for post-mortem analysis when tracking issues arise in the field.

By following these principles and leveraging the right combination of engines, SDKs, and toolchains, software developers can deliver robust and high-fidelity AR applications that perform well across devices and use cases.

1.1.3. User Adoption

User adoption of augmented reality depends on perceived value, ease of use, trust, and support. The key factors and strategies include [20]:

- Perceived Usefulness and Relevance

Tailored AR experiences to real user needs can be used in training, maintenance, retail visualization, and navigation.

Return on investment (ROI) can be demonstrated through case studies and pilot programs before full deployment.

- Ease of Use and Onboarding. Intuitive user interfaces with familiar gestures and minimal steps improve user efficiency.

Step-by-step tutorials, contextual tooltips, and guided tours on the first use ensure successful operation.

- Trust and Reliability. Stable tracking, fast load times, and accurate overlays build user's confidence.

Users should be clearly informed about data usage and privacy policies and be able to opt-in controls for location and camera access.

- Learning Curve and Training.

Micro-learning modules and in-app help for new users to delve into the subject.

Gamification (e.g., badges, leaderboards, and achievement tracking) motivates users' exploration activities.

- Accessibility and Inclusivity.

Hardware and Software should support multiple input methods (touch, voice, gestures) and adapt to different physical users' abilities.

Localized languages and cultural assets advance people's communication.

- Social Proof and Network Effects

Sharing AR content on social media and collaboration features for teams encourage the further development of AR technologies.

Early adopters and influencers can generate word-of-mouth referrals to popularize AR.

- Incentives and Business Models

Freemium or trial models can decrease entry barriers.

Discounts, loyalty rewards, or exclusive virtual content activate users' interest and attention.

- Technical Support and Community

Maintaining active support channels, including forums, chatbots, and help desks, facilitates user engagement and promotes the adoption of AR technologies.

Developer and user communities, where tips, custom assets, and extensions can be shared, help users exchange information.

- Performance Monitoring and Iteration

Monitoring metrics, such as session duration, feature utilization, task completion rates, and drop-off points, provides a foundation for evaluating the effectiveness of AR systems.

A/B testing can be used to refine onboarding flows, UI layouts, and content relevance.

- Long-Term Engagement

Regularly updated AR content should be implemented according to user feedback and emerging needs.

Seasonal or thematic experiences can be organized to re-engage dormant users.

By addressing factors such as efficiency, productivity, usability, and continuous improvement, researchers can promote higher adoption rates and sustained use of AR solutions.

1.2. Environmental Conditions

Environmental conditions play a critical role in the performance of AR systems (Figure 2).

In particular, fluctuations in illumination can significantly degrade the quality of the input data by introducing sensor noise, reducing image contrast, and impairing the robustness of object detection and recognition algorithms. Variations in lighting may arise from natural sources (e.g., sunlight intensity changes and shadows) or artificial sources (e.g., indoor lighting flicker and reflections), and these factors directly affect the accuracy of feature extraction and tracking.

To mitigate these effects, AR systems employ reliable computer vision techniques, such as adaptive histogram equalization, denoising filters, and photometric normalization. Furthermore, multi-sensor fusion strategies that combine visual data with inertial or depth sensors are increasingly adopted to ensure robust performance under varying environmental conditions. These approaches enable AR systems to maintain stability, accuracy, and usability in real-world scenarios.

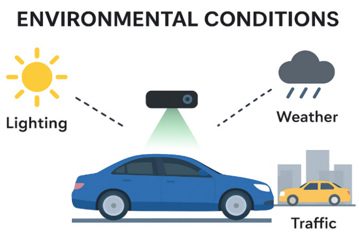

Figure 2. Environmental conditions

Source: by F.K. Ceesay.

2. Formation of the Augmented Reality Systems

The algorithm for AR system formation is based on the integration of multiple computational and perceptual processes that ensure robust, context-aware augmentation of the physical environment.

The formation process can be divided into four major stages:

– processing environmental conditions, includeing improving the images with methods of denoising and contrast enhancement;

– creating a model of the surrounding space;

– generating digital content;

– placing digital content in the modelled space.

2.1. Processing Environmental Conditions

The Processing Environmental Conditions algorithm is designed to enhance and normalize visual data captured from vehicle-mounted cameras or other environmental sensors operating under varying lighting and weather conditions (Figures 3 and 4). Its primary objective is to improve the image quality, visibility, and reliability for downstream applications such as AR spatial modelling, autonomous navigation, and environmental visualization.

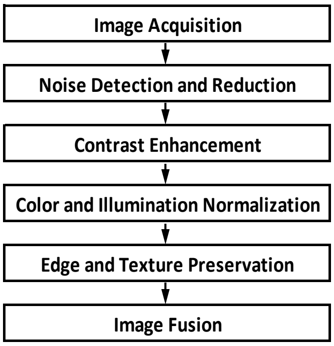

Figure 3. Algorithm: processing environmental conditions

Source: by F.K. Ceesay.

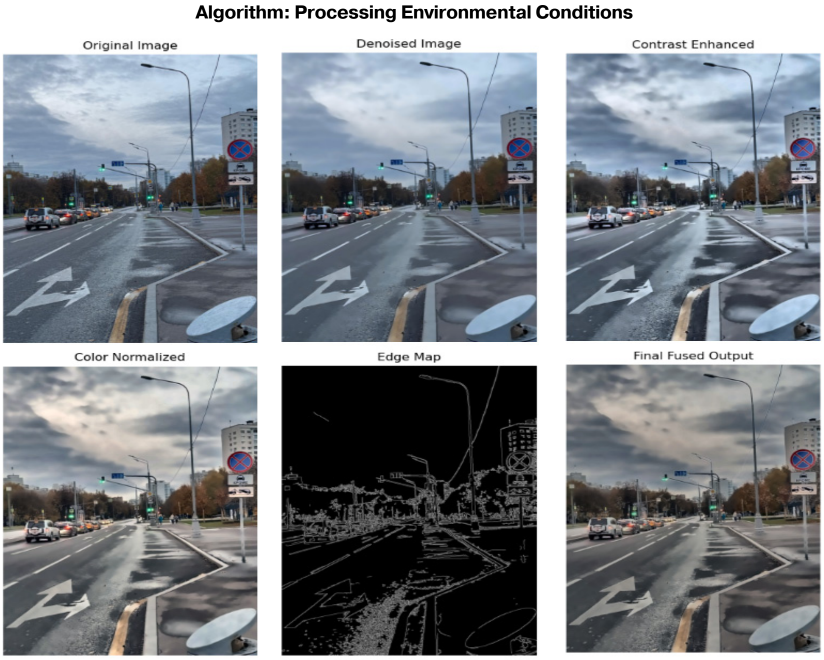

Figure 4. Result of algorithm: processing environmental conditions
Source: by F.K. Ceesay.

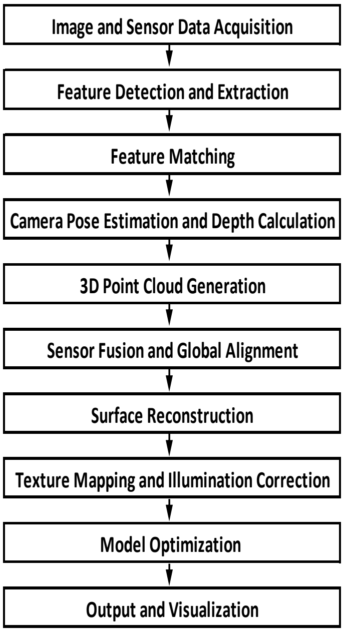

Figure 5. Algorithm: creating a model of the surrounding space
Source: by F.K. Ceesay.

This algorithm performs a sequence of image-processing operations to remove unwanted noise, improve contrast, balance illumination, and preserve essential visual features, such as edges and textures. By fusing enhanced color and edge information, the algorithm produces a high-quality image output suitable for accurate spatial interpretation and object recognition in dynamic environments.

2.2. Creating a Model of the Surrounding Space

This algorithm simulates the process of **creating a *3D spatial model of an environment*** from a single image (as if captured by a vehicle-mounted camera or drone) (Figures 5 and 6).

It extracts features, generates depth, and visualizes the ***3D point cloud***.

Figure 6. Result of the algorithm: creating a model of the surrounding space
Source: by F.K. Ceesay.

2.3. Generating Digital Content

The algorithm is a simulation that generates and visualizes **digital content** (such as AR objects) placed in a **3D spatial environ**ment (Figures 7, 8**)**. It uses environmental data (weather, light, and temperature) to decide what kind of digital content to place and where. Finally, everything is rendered in a **3D plot**.

2.4. Placing Digital Content in the Modelled Space

The algorithm generates a 3D terrain, detects flat areas suitable for placing digital content, selects content based on environmental conditions (such as weather), assigns the content to those flat regions, and visualizes everything in a 3D plot (Figures 9, 10).

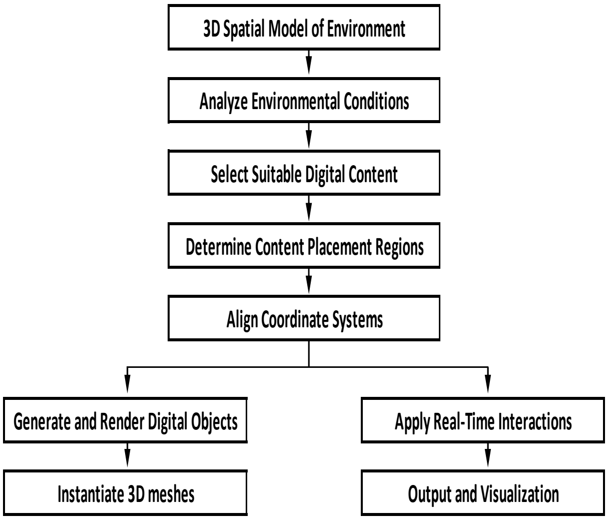

Figure 7. Algorithm: generating digital content
Source: by Fafa K. Ceesay.

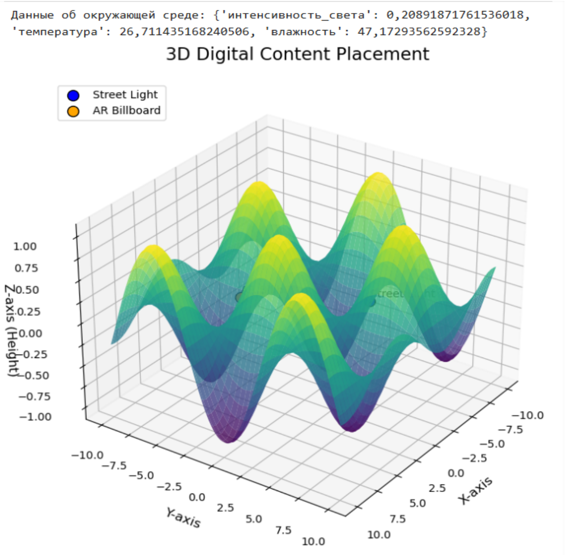

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Figure 8. Result of the Algorithm: Generating digital content
Source: by F.K. Ceesay.

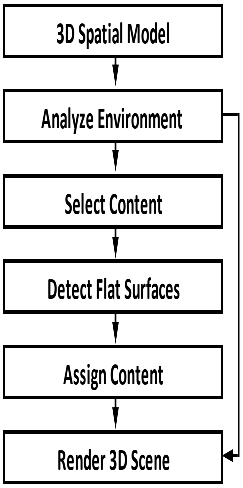

Figure 9. Algorithm:
Place digital content in modelled 3D space
Source: by F.K. Ceesay.

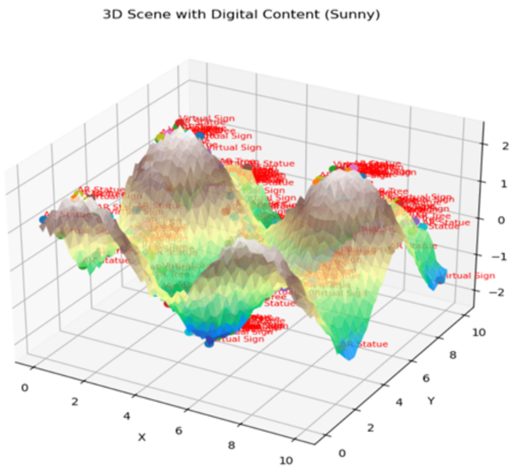

Figure 10. Result of the algorithm:
place digital content in modelled 3D space
Source: by Fafa K. Ceesay.

3. Results

The analysis shows that the formation of Augmented Reality systems is not driven by a single determinant but emerges from the interaction of eight classes of factors.

First, hardware constraints (processor performance, display type, battery capacity, and sensor fidelity) establish the physical and computational limits of the system.

Second, tracking and registration accuracy, governed by the tracking strategy, environmental cues, and latency, directly affects the stability and utility of the augmentations.

Third, software architecture and platform choices, including framework selection, operating system support, and cloud/on-device distribution, shape the system's extensibility and real-time behavior.

Fourth, human — computer interaction factors, such as the field of view, interaction modality, ergonomics, perceptual comfort, and cognitive load, determine how augmentation can be safely and effectively consumed by users.

Fifth, the content and experience design requirements (realism level, scene understanding depth, dynamicity, and multi-user support) influence both the data pipelines and runtime complexity.

Sixth, environmental conditions, particularly lighting, texture richness, and outdoor variability, mediate the reliability of perception and alignment.

Seventh, business and ecosystem forces, inclu-ding the target industry, integration cost, and market maturity, constrain viable design trade-offs.

Finally, considerations related to privacy, security, and ethics, particularly continuous sensing and bystander exposure, establish normative and regulatory constraints on the development of AR systems. Collectively, these factors shape the technical architecture, define the boundaries of usability, and influence the feasibility of AR deployment.

4. Discussion

The program's performance and efficiency confirm the effectiveness of the proposed method for processing environmental data in combination with the fused data from object-mounted sensors.

The results of the developed AR system confirm the feasibility of using a combined pipeline of image preprocessing, environment modeling, digital content generation, and spatial placement for effective augmented reality applications. Several aspects merit further discussion.

1. *Robustness under environmental conditions*: The system demonstrated resilience to fluctuations in illumination and noise through preprocessing methods such as denoising and Contrast Limited Adaptive Histogram Equalization (CLAHE). This confirms earlier findings that reliable preprocessing is essential for object detection and AR overlay stability.

2. *Accuracy of environment modeling:* The integration of vision-based reconstruction with multisensor fusion yielded a more stable and accurate digital model of the surrounding space. This supports the claims in the literature that combining camera vision with IMU or depth data enhances spatial consistency.

3. *Real-time performance:* Experimental results show that the pipeline can operate in real time, although the computational demands increase with higher resolution inputs and more complex overlays. This balance between speed and fidelity is a common challenge in AR development.

4. *User-centered functionality:* The program's ergonomic and accessibility features make it adaptable to various user groups. However, large-scale usability studies are required to fully validate these claims.

5. *Limitations:* Despite its robustness, the system faces challenges in highly dynamic environments, where rapid motion and occlusions reduce feature-matching accuracy. Additionally, sensor calibration remains critical for maintaining spatial alignment.

6. *Future Directions:* Future work should focus on optimizing computational efficiency using GPU acceleration, expanding multi-sensor integration (e.g., LiDAR), and improving the semantic understanding of the environment for context-aware AR overlays.

Conclusion

The formation of AR systems is shaped by a multifaceted array of factors that collectively influence their development, adoption and effectiveness. Technological advancements serve as primary drivers, enabling more sophisticated hardware and software solutions that enhance user experience and broaden the applicability of AR across various sectors.

Understanding these factors is essential for stakeholders in the AR ecosystem, including scientists, developers, and programmers. By recognizing and addressing these influences, they can create more effective, user-centered AR solutions that not only meet market demands but also foster broader acceptance and integration of augmented reality into everyday life. As AR continues to evolve, the interplay of these various factors will remain critical in shaping its future trajectory and potential impact on society.

This study has presented the development and evaluation of an algorithm for the formation of AR systems. The proposed pipeline, consisting of environmental preprocessing, modeling of the surrounding space, digital content generation, and spatial placement, demonstrated its effectiveness in creating a stable and functional AR environment.

Key Findings:

Robustness to environmental conditions: Preprocessing techniques, such as denoising and CLAHE, significantly improved visual clarity, ensuring reliable performance under fluctuating lighting and noise.

Improved environmental modeling: The integration of computer vision techniques with multisensor fusion enabled the creation of accurate and stable digital representations of the physical environment.

Real-time capability: The system successfully achieved real-time performance, making it suitable for interactive applications.

Usability and ergonomics: The program was designed using user-centered principles to enhance ease of use, accessibility, and safety.

Future Work. Despite these achievements, some limitations remain, including challenges in highly dynamic scenes and the need for precise sensor calibration. Future studies should explore GPU acceleration, semantic environment understanding, and broader usability testing to further enhance the robustness and adaptability of AR systems.

In conclusion, the developed AR system confirms the feasibility of combining advanced computer vision with sensor fusion to achieve practical, robust, and user-friendly augmented reality applications.

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