University of the Philippines Cebu
College of Science
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KamayAR: Advancing Communication Through AR-Based Sign Language Gesture Recognition and Text to Gesture Implementation

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CHAPTER 1

INTRODUCTION

1.1 Rationale

In recent years, technological advancements have revolutionized the way humans interact and communicate, particularly through innovative solutions like augmented reality (AR). Despite the rapid development of image processing and machine learning technologies globally, individuals with disabilities continue to face significant barriers due to the high costs of specialized devices (Copley & Ziviani 2004) and limited accessibility to assistive technologies (World Health Organization, 2022). The World Health Organization (2022) reports that over 430 million people worldwide experience disabling hearing loss, highlighting the urgent need for accessible communication solutions. As Mary Pat Radabaugh, formerly with the IBM National Support Center for Persons with Disabilities, eloquently noted, "For most people, technology makes things easier. For people with disabilities, technology makes things possible”. This growing concern has prompted researchers and developers to explore innovative approaches that leverage existing technologies to create more affordable and accessible communication tools, particularly focusing on the integration of AR technology into widely available mobile devices.

The integration of augmented reality in assistive technologies has shown promising results in breaking down communication barriers. In particular, the development of AR applications for mobile devices offers a sustainable approach to address accessibility challenges, making specialized communication tools more attainable for marginalized communities. Recent studies indicate that AR-based assistive technologies can significantly improve the quality of life for individuals with hearing and speech impairments when implemented effectively (Marwah et al., 2024). However, the successful implementation of these technologies requires careful consideration of various factors, including technological infrastructure, user accessibility, and economic feasibility across different regions. Understanding these dynamics at various geographical levels has become crucial in developing practical solutions that can effectively serve the deaf-mute community while ensuring sustainable and inclusive technological advancement.

On a global scale, the deployment of AR-based assistive technologies faces both opportunities and challenges. The International Telecommunication Union reports that approximately 85% of the world's population now has access to mobile broadband networks (ITU, 2020), creating potential pathways for AR-based solutions. However, among the estimated 70 million deaf people worldwide who use sign language as their primary means of communication (Gupta et al., 2004), only a small fraction has access to quality education and assistive technologies. This disparity is particularly evident in developing nations, where limited resources and infrastructure constraints hinder the adoption of innovative assistive solutions (Raja, 2016). The economic barriers between technological advancement and accessibility continue to widen, especially in low and middle-income countries, highlighting the urgent need for more affordable and adaptable solutions that can leverage existing mobile infrastructure.

In response to these global challenges, researchers worldwide have begun developing innovative AR-based solutions to bridge the communication gap. A notable breakthrough in this field is the LEARNSIGN project by Rum et al. (2021), which successfully integrated AR with speech recognition to facilitate real-time sign language communication. Their research demonstrated that AR technology, when properly implemented, can provide practical and cost-effective solutions for everyday interactions within the deaf-mute community. This advancement, along with similar initiatives worldwide, suggests that mobile-based AR applications could offer a viable pathway to address the accessibility challenges faced by hearing-impaired individuals across different socioeconomic backgrounds.

In the Philippines, AR-based assistive technologies have gained traction, driven by the country's increasing focus on leveraging mobile technologies to address accessibility gaps. Mendoza et al. (2024) have developed a pioneering sign language text translator that uses the YOLOV7 algorithm, demonstrating the integration of advanced machine learning techniques with AR to enhance the accuracy of real-time sign language interpretation. This innovation aligns with the nation's goal to bridge the digital divide and empower underserved populations, especially within the deaf-mute community. The localized applications of AR not only reflect the Philippines' capacity for technological innovation but also underscore the critical role of contextually relevant solutions in addressing accessibility challenges unique to the region.

Locally, In Central Visayas, where Cebu is a significant economic and cultural hub, communication barriers remain a pressing issue for the deaf-mute community. Based on data from the Philippine Statistics Authority (PSA), approximately 575,242 individuals, or 7.96% of the region's household population, have at least one functional difficulty, including hearing impairments (PSA, n.d.). Despite Cebu's rapid technological growth and its emergence as a key innovation center, assistive technologies that specifically address the needs of individuals with disabilities remain underdeveloped and inaccessible to many. This study introduces " KamayAR" an augmented reality application designed to provide real-time sign language interpretation tailored to the Cebuano context. By leveraging widely accessible mobile devices, KamayAR aims to bridge communication gaps, enhancing inclusivity and participation for the deaf-mute community in Cebu. This initiative aligns with regional efforts to integrate technology into daily life, promoting equal opportunities for all residents.

1.2 Statement of the Problem

Despite significant advancements in communication technology, the deaf and mute community continues to face substantial barriers to effective interaction. Existing communication tools often fall short in providing real-time, seamless translation of spoken language into gestures, necessitating manual interpretation or complex setups that hinder spontaneous communication. This gap in technology impacts daily interactions, leading to communication barriers that can isolate individuals and restrict their participation in social and professional environments.

Augmented Reality (AR) has demonstrated potential across various domains, including enhancing communication for the deaf and mute. For instance, TranscribeGlass is an AR tool that attaches to any pair of glasses and projects real-time subtitles in the user’s field of vision, facilitating more accessible communication for individuals with hearing impairments (TranscribeGlass, n.d.). Similarly, XRAI Glass has developed AR smart glasses that allow deaf people to "see" conversations in real-time by converting audio into captions displayed directly in the user's line of sight (Hill, 2022). These innovations highlight the transformative potential of AR in bridging communication gaps.

However, the adoption of AR technologies in everyday life, especially in developing countries like the Philippines, is hampered by a lack of infrastructure, awareness, and localized content. Studies have identified critical barriers to AR technology adoption in developing countries, such as high costs, limited technological awareness, and insufficient government support (Oke and Arowoiya, 2021). Moreover, existing studies on AR applications for the deaf and mute often focus on isolated scenarios or controlled environments, with little attention given to scalable, user-friendly solutions that can be implemented in diverse real-world settings (Borna et al., 2024).

To address these issues, this research proposes the development of "KamayAR an AR application tailored to meet the specific communication needs of the deaf and mute community in the Philippines. By leveraging cutting-edge AR technology, KamayAR aims to bridge the communication gap by providing real-time, intuitive translation services that are culturally and linguistically appropriate for its users.

1.3 Research Objectives

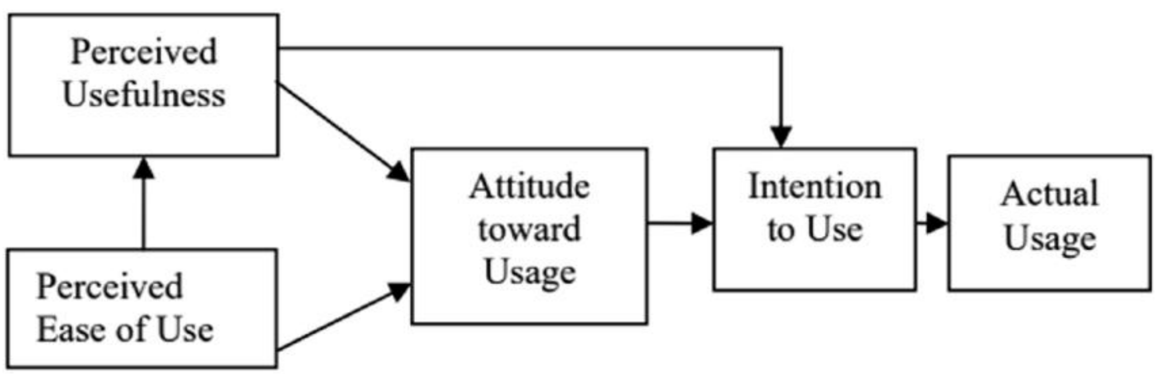
This study aims to improve communication for the deaf/mute community by developing a user-friendly, AR-based mobile application (KamayAR) that accurately recognizes sign language gestures and translates them into text. By enhancing translation accuracy, processing speed, and overall usability, this research seeks to create a tool that promotes more inclusive, accessible, and engaging interactions within diverse social and educational settings. Specifically, this study will:

- Develop a real-time AR mobile application capable of accurately recognizing and translating sign language gestures into text.

- Optimize translation processing speed to ensure seamless, real-time communication.
- Evaluate user experience to improve usability, user satisfaction, and practical utility in everyday interactions.
- Assess the application's effectiveness as a learning aid for basic sign language skills and its overall impact in real-world scenarios.

1.4 Theoretical Framework

The development of an Augmented Reality (AR) system for sign language translation in this study is fundamentally anchored in the Technology Acceptance Model (TAM). Originally proposed by Davis (1989), TAM stands as a well-established theoretical framework for predicting how individuals adopt and effectively use new technologies. It places particular emphasis on two primary constructs—perceived usefulness and perceived ease of use—both of which have been shown to play a pivotal role in shaping user acceptance, as illustrated in Figure 1.



Source(s): Davis (1989)

Figure 1. Technology Accepted Model (Davis, 1989)

In this context, TAM is especially relevant as it provides insight into how members of the deaf and mute community, as well as potential hearing users, might evaluate an AR-based sign language translator designed for real-time interactions. Their perceptions of the application's effectiveness in accurately converting gestures into text, combined with its ease of operation on everyday mobile devices, are expected to significantly influence their willingness to adopt this technology. Factors such as familiarity with mobile interfaces, the clarity of instructions within the AR environment, and the reliability of gesture detection all contribute to how useful and user-friendly individuals perceive the system to be.

Moreover, perceived ease of use emerges as a critical consideration for this study's target users. Many individuals in the deaf and mute community rely on accessible, intuitive tools for their daily communication needs. A system that requires minimal technical expertise can help them feel confident in navigating the AR interface, thus reducing barriers to adoption. By combining technical sophistication—such as accurate sign language recognition and real-time translation—with a user-centric design, the application stands a better chance of achieving both efficacy and acceptance.

By applying TAM, this study aims to assess the likelihood of adoption and ongoing use of the AR-based sign language translator, which is central to fostering inclusive communication. A strong focus on user acceptance ensures that the system will not only demonstrate advanced technical capabilities but also integrate seamlessly into the community's everyday experiences. Through this lens, the research ultimately seeks to enhance communication opportunities for the deaf and mute population, thereby contributing to a more inclusive society.

1.5 Significance of the Study

The AR-based sign language translation application developed in this study is expected to benefit various stakeholders within the Filipino community and beyond:

- **Deaf and Mute Community:** The application aims to facilitate more inclusive daily interactions by providing real-time, accessible communication support. By bridging the language gap and enabling more fluid exchanges, it empowers individuals to participate more fully in social, educational, and professional settings, thereby improving their overall quality of life.
- **Educational Institutions and Training Centers:** Schools, universities, and language training centers can integrate the application into their programs to enhance the learning experience of both hearing and non-hearing students. This practical exposure to AR-assisted translation fosters a deeper understanding of sign language, encourages empathy, and nurtures a generation of professionals prepared to promote inclusivity.
- **Organizations and Agencies Supporting Accessibility:** Nonprofit organizations, advocacy groups, and government agencies focused on disability inclusion may incorporate this technology into their initiatives. By offering a practical, user-friendly tool, they can strengthen efforts aimed at improving access to essential services, ensuring that effective communication is no longer a barrier to participation in civic life and community development.
- **Developers and Researchers in Assistive Technologies:** The insights gained from designing and testing this application provide valuable knowledge for future research and development in the field of AR-based assistive tools. These findings

may inspire further innovation, guide improvements in gesture recognition accuracy and response speed, and ultimately contribute to a richer ecosystem of accessible technologies.

- **General Public:** By showcasing how AR and machine learning can address real-world communication challenges, this study helps raise public awareness about the transformative potential of emerging technologies. This broader understanding can encourage more inclusive community perspectives and highlight the importance of investing in solutions that uplift marginalized groups, contributing to a more equitable society.

1.6 Scope and Delimitations

This study focuses on developing and evaluating "KamayAR," a mobile augmented reality application that provides two primary features for facilitating real-time communication between spoken English and American Sign Language (ASL). Implemented using Unity, the application is optimized for smartphones equipped with AR capabilities. At this stage, the scope is intentionally limited to English for the spoken and written component and ASL for the gesture component, ensuring a concentrated effort on refining the system's core functionality.

Within this framework, the target object of the study encompasses two interactive modes. First, the Text-to-Gesture mode allows users to input English text (either typed or spoken), which KamayAR then translates into AR-rendered ASL gestures displayed onscreen. Second, the Gesture-to-Text mode captures a user's ASL gestures via the smartphone camera and converts them into English text in real time. The application interface features streamlined screen transitions and simplified controls to cater to users with diverse technical backgrounds, while also enhancing the immediacy of communication.

To ensure cultural and linguistic accuracy, the gesture library is focused on everyday vocabulary and common phrases, and its development will be guided by an experienced ASL professional who leads a local organization for the deaf and mute community. This collaboration offers critical insights into sign selection and interface design, making the application more accessible to the intended user base.

Due to time constraints and the need to collect high-quality, targeted feedback, testing will be conducted with a relatively small group of participants, including members of the aforementioned organization and additional ASL users in the area. Although this approach provides immediate, context-specific evaluation, it inherently restricts the generalizability of findings to a broader population or other sign languages. Furthermore, the technical performance of KamayAR depends on factors such as Unity's AR toolkit and varying smartphone specifications (camera resolution, processing power), as well as environmental elements like lighting and background noise. These practical considerations serve as delimitations, shaping the study's outcomes and underscoring the importance of iterative development and future scalability.

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CHAPTER 2

REVIEW OF RELATED LITERATURE

Augmented Reality

The evolution of augmented reality (AR) marks a significant milestone in human-computer interaction, transforming how we perceive and interact with our environment. Since its conceptual introduction by Ivan Sutherland in 1968 with the first head-mounted display system, AR has grown from an experimental technology into a powerful tool that seamlessly blends digital information with the physical world (Billinghurst et al., 2015). This technology enhances real-world environments by overlaying computer-generated content, including images, sounds, and interactive data, creating an enriched sensory experience that has found applications across numerous fields, from medicine to education (Azuma et al., 1997). The advancement of AR technology has been particularly accelerated by improvements in computer vision, sensor technology, and processing capabilities, enabling more sophisticated and responsive augmented experiences.

Mobile Augmented Reality

The emergence of mobile augmented reality (MAR) has democratized access to AR technology, transforming smartphones and tablets into powerful platforms for augmented experiences. A study by Dunleavy and Dede (2014) highlighted how the ubiquity of mobile devices, equipped with high-resolution cameras, powerful processors, and sophisticated sensors, has created unprecedented opportunities for AR application development and deployment. Mobile AR applications leverage these built-in capabilities to provide context-aware, real-time augmentation that can be accessed anywhere, significantly reducing the barriers to AR technology adoption. The shift from specialized AR hardware to mobile platforms has not only made AR more accessible but has also fostered innovation in application development, particularly in areas requiring real-time interaction and environmental awareness.

Assistive Technology

While mobile AR continues to evolve, another significant technological domain that has transformed lives is assistive technology. The World Health Organization (2022) defines assistive technology as any device, system, or equipment that maintains or improves an individual's functioning and independence, thereby promoting their well-being. Over the past decades, assistive technologies have progressed from simple mechanical devices to sophisticated digital solutions, marking a significant shift in how technology can support individuals with disabilities. According to the United Nations Department of Economic and Social Affairs (n.d.), approximately 1.3 billion people globally need assistive technology, yet only one in ten people have access to the assistive products they require. This gap between need and access has driven continuous innovation in the field, particularly in developing more affordable and accessible solutions that can leverage existing technology infrastructure.

AR-Based Assistive Technologies for the Deaf-Mute Community

The integration of AR into assistive technologies has revolutionized support systems for the deaf-mute community, offering innovative solutions for real-time communication challenges. Studies have shown that AR-based assistive technologies can significantly enhance communication effectiveness while reducing dependency on human interpreters (Ridha and Shehieb., 2021). These technologies not only provide immediate translation capabilities but also help preserve the nuances of sign language, which is crucial for maintaining cultural and linguistic identity within the deaf community (Rodríguez-Correa et al., 2023). Furthermore, the accessibility of AR through mobile devices has made these solutions more economically viable and widely available compared to traditional assistive devices (Creed et al., 2024).

In recent years, several groundbreaking projects have demonstrated the practical application of AR in sign language communication. The LEARNSIGN project by Rum et al. (2021) represents a significant advancement in this field by developing an AR-based interactive Malaysian Sign Language learning platform. Their system integrated augmented reality with speech recognition to provide users with visual sign language learning materials, aiming to make sign language learning more engaging and interactive. While the system showed promise in educational settings, it also highlighted the ongoing challenges in creating comprehensive AR-based sign language learning tools, particularly in addressing the diverse needs of different user groups and maintaining consistent performance across various usage scenarios.

Following LEARNSIGN's contribution to sign language education, Leeson and Haaris (2009) introduced a mobile application that utilizes computer vision and machine learning for real-time sign language translation. Their system demonstrated practical success in translating American Sign Language (ASL) to text with documented user trials across multiple US educational institutions. However, the application faced challenges with processing speed on lower-end mobile devices and required specific lighting conditions for optimal performance.

Another notable advancement came from Google's SignTown project (2021), which employed MediaPipe's machine learning framework to create a browser-based sign language learning game. While the project successfully achieved real-time hand gesture recognition and made sign language learning more interactive, it faced several limitations. The system's browser-based nature restricted mobility and accessibility compared to mobile applications, required consistent internet connectivity for operation, and struggled with recognizing complex sign language phrases. Additionally, the lack of a mobile platform significantly limited its practical use in real-world scenarios where immediate translation might be needed

These pioneering projects in AR-based sign language systems have not only demonstrated the technology's potential but have also highlighted the critical importance of mobile accessibility in creating practical solutions for the deaf-mute community. Their successes and limitations have paved the way for understanding how AR technology can be effectively implemented to address communication barriers. The advantages of using AR-based systems specifically designed for mobile platforms extend far beyond mere convenience.

Advantages of Mobile AR-Based Systems for the Deaf-Mute Community

The implementation of mobile AR-based systems offers multifaceted benefits that directly address the communication challenges faced by the deaf-mute community. These systems provide immediate, portable translation capabilities that can be accessed through commonly available smartphones, making assistive technology more affordable and accessible compared to specialized devices (Kamaluddin, 2024). A study by Borna et al., (2024) have shown that mobile AR applications can significantly reduce communication barriers in various settings, from educational environments to healthcare facilities, enhancing both independence and social integration for individuals who are deaf or mute. Furthermore, the real-time processing capabilities of modern mobile devices, combined with AR visualization, create a more natural and intuitive communication experience that benefits both the deaf-mute community and those interacting with them, fostering greater social inclusion and equal participation in daily activities.

In conclusion, the reviewed literature illustrates the transformative potential of AR technology in addressing communication barriers for the deaf-mute community. From its evolution into mobile platforms to its integration with assistive technologies, AR has shown promising applications in creating more accessible and practical communication solutions. While existing projects such as LEARNSIGN and SignTown have made significant strides in implementing AR for sign language translation and learning, they have also revealed important challenges that need to be addressed. These challenges, including recognition accuracy, mobility limitations, and real-world performance variations, provide valuable insights for developing more effective mobile AR-based solutions. Although there may be limitations in current implementations, the documented advantages of mobile AR systems suggest a promising direction for creating more inclusive communication tools. These studies collectively inform the development of KamayAR, particularly in addressing the identified gaps while building upon the successful aspects of existing solutions.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Research Design

This study employs the iterative waterfall model as its software development methodology, a systematic approach that allows for continuous refinement while maintaining structured development phases. The iterative nature of this model enables the researchers to revisit and improve each phase based on feedback and testing results, particularly crucial for developing an AR-based sign language translation system that requires precise gesture recognition and real-time processing. This methodology comprises five main phases: Requirement Analysis, System Design, Development, Testing, and Deployment, as illustrated in Figure 2.

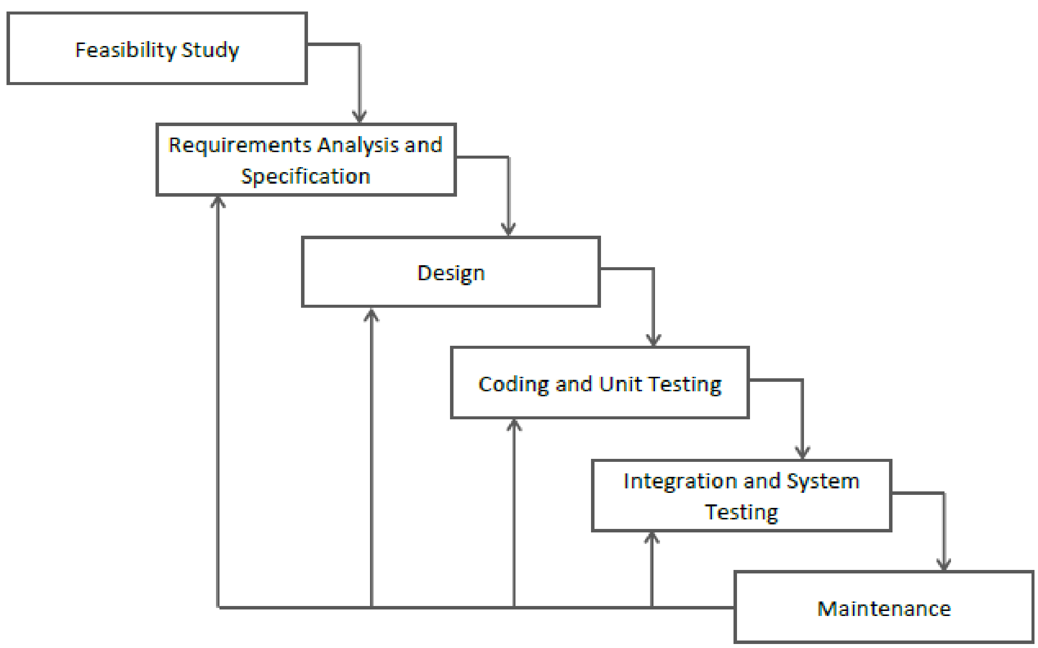

Figure 2. Iterative Waterfall Model

3.1.1 Requirement Analysis and Specification

In the initial phase of the project, comprehensive requirements are gathered through analysis of existing AR-based sign language systems, and consultation with potential users from the deaf-mute community. This phase focuses on identifying essential features, technical requirements, and user expectations for the KamayAR application. The researchers conduct systematic documentation of functional requirements, including sign language recognition parameters, translation accuracy requirements, and user interface specifications.

3.1.2 System Design

In this phase, it utilized the compiled requirements to develop a structured framework for the KamayAR mobile application. This phase focused on creating an efficient and user-friendly system that could effectively translate sign language through augmented reality on Android devices. The researchers established the core functionalities, including real-time gesture recognition, AR visualization, and translation processing. The process involved mapping out the application's workflow and user interaction patterns, followed by designing intuitive interfaces that accommodate both the deaf-mute community and other users. The researchers utilized Figma, a collaborative interface design tool, to create both low-fidelity wireframes and high-fidelity interactive prototypes, ensuring proper implementation of Material Design principles and accessibility guidelines. This prototyping phase was crucial in visualizing user interactions and gathering early feedback on the interface design before proceeding with actual development.

3.1.3 Coding and Unit Testing

This phase implemented the designed system using Unity as the primary development platform, leveraging its robust AR capabilities and cross-platform development features. The researchers utilized existing libraries and datasets for sign language recognition to ensure reliable gesture detection and translation accuracy. The application was developed to process all translations locally on the device, ensuring functionality without internet connectivity and maintaining user privacy. The development process involved multiple iterations, with each cycle focusing on implementing and refining specific features such as camera feed processing, gesture recognition, and AR visualization. The user interface was constructed using Unity's UI framework, ensuring consistent design implementation across different Android devices while maintaining optimal performance.

3.1.4 Integration and System Testing

The testing phase encompassed comprehensive evaluation of KamayAR's functionality and performance across different Android devices. The researchers conducted systematic testing of individual components, including gesture recognition accuracy, AR visualization performance, and user interface responsiveness. Integration testing focused on ensuring seamless interaction between various modules, particularly the coordination between camera input, gesture recognition, and AR overlay display. The application underwent multiple testing iterations with each development cycle, allowing for continuous refinement of features and resolution of identified issues.

3.1.5 Maintenance

The deployment phase will focus on the final implementation and release of the KamayAR application to target users. After successful testing and refinement, the application will be prepared for distribution by optimizing the build settings in Unity for Android platform deployment. Following deployment, the system will be monitored for any potential issues or necessary improvements that might arise from actual usage. This phase will also include the preparation of basic documentation to guide users in installing and utilizing the application effectively on their Android devices.

3.2 Research Participants

In alignment with the study's scope and delimitations, participants will be drawn from two main groups. The first group consists of a professional American Sign Language (ASL) interpreter, together with approximately ten members of her organization supporting the deaf and mute community. These participants are critical for validating the application's gesture-to-text functionality and ensuring cultural and linguistic accuracy. The second group comprises around ten to fifteen individuals from the University of the Philippines Cebu, who are not members of the deaf and mute community. Their inclusion provides additional perspectives on the text-to-gesture feature and user interface from a general public standpoint.

No strict prerequisites regarding age or technical background will be imposed, thereby capturing a range of user experiences and competencies with AR technology. Testing will be conducted both in-person—at the organization's facilities and designated spaces within the university—and remotely for those unable to attend physically. During these sessions, participants will perform specific tasks designed to assess both core features: translating spoken or typed English into AR-rendered ASL gestures and converting ASL gestures into text. Following each task, users will complete brief surveys evaluating the system's accuracy, ease of use, and overall satisfaction. These findings will inform iterative refinements and help ensure that KamayAR meets the practical needs and expectations of both ASL-reliant users and the broader public.

3.3 System Modules

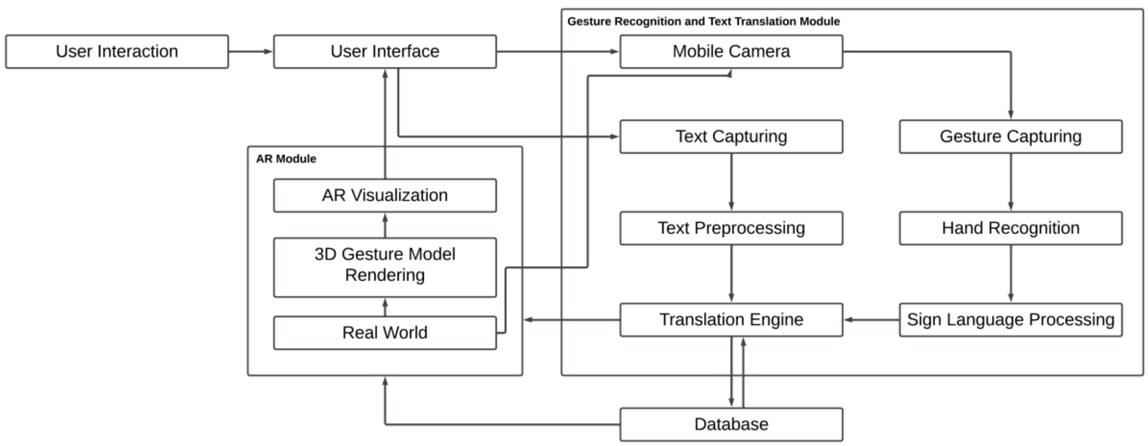

Figure 3. System Architecture

Figure 3 illustrates the proposed architecture of the "KamayAR" application, designed to facilitate both text-to-gesture and gesture-to-text translations using augmented reality. The system is organized into five primary components: User, User Interface, Gesture Recognition and Translation, AR Module, and Database. Each component is structured to deliver seamless communication support for both deaf/mute and hearing users, ensuring accurate translations and intuitive 3D visualizations of American Sign Language (ASL) gestures.

3.3.1 User

The User is the core stakeholder who interacts with KamayAR to either convert typed/spoken English into ASL gestures or translate signed gestures into text. Users may belong to the deaf/mute community or be hearing individuals looking to communicate more effectively. Their input—whether it is text entry, spoken language, or live ASL gestures—initiates the system's workflow.

3.3.2 User Interface Module

The User Interface (UI) serves as the gateway between the user and the underlying modules. It provides an accessible layout where users can:

- Select the translation mode (Text-to-Gesture or Gesture-to-Text).
- Type English phrases.
- View the real-time AR animations of ASL gestures or on-screen text outputs.

Through clear visual prompts and minimal, intuitive controls, the UI accommodates various skill levels and technical backgrounds. It is also responsible for relaying relevant status messages, such as "translation in progress," or guidance on improving gesture clarity, ensuring an engaging and user-friendly experience.

3.3.3 Gesture Recognition and Translation Module

The Gesture Recognition and Translation module processes input from two sources—live video of signed gestures and user-entered text—transforming them into meaningful, context-appropriate outputs. For gesture-to-text conversions, video captured by the smartphone camera undergoes basic preprocessing to isolate and track hand movements. Computer vision or machine learning algorithms then identify the detected gestures and map them to corresponding English words or phrases, subsequently relaying the results to other system components. For text-to-gesture operations, typed or spoken English phrases are parsed and segmented before they are matched against stored ASL data. This module thus forms the operational core of KamayAR, integrating both pathways to enable bidirectional communication.

3.1.4 AR Module

The AR Module is responsible for blending digital sign language representations with the user's immediate surroundings, creating an immersive and interactive environment. Upon receiving instructions from the Translation Engine, this module retrieves or generates the appropriate 3D gesture models. These models are then superimposed onto the smartphone's camera feed, maintaining realistic scaling and alignment so the user can perceive the rendered signs in real-time. By overlaying accurate, dynamically generated ASL gestures onto the actual environment, this module significantly improves the usability and learning potential of KamayAR, enabling users to observe and replicate the nuances of each sign with minimal confusion.

3.1.5 AR Database

The Database stores all necessary resources for the translation and visualization processes, ensuring swift retrieval and updates. It maintains a comprehensive library of ASL gesture models, their associated English keywords or phrases, and any relevant metadata, such as sign variations or cultural notes. This repository may also keep user preferences or logs of past translations, providing opportunities for personalization and iterative enhancement of the system. Through this centralized structure, both the Gesture Recognition and Translation module and the AR Module can quickly access the data they need, facilitating a cohesive workflow that remains efficient and scalable.

3.4 Operation Modules

The following operations were undertaken in the creation of the application:

1. **UI/UX Ideation**
   - **1.1.** Designing low-fidelity wireframes using Figma to visualize core user flows.
   - **1.2.** Creating high-fidelity prototypes in Figma adhering to Material Design principles for accessibility.
   - **1.3.** Structuring the interactive interface for the text-to-sign translation feature, prioritizing usability and AR visualization.
2. **Setting Up Development Environment**
   - **2.1.** Installation and setup of Unity as the primary development platform for the AR features.
   - **2.2.** Creation and management of a Git repository for version control.
   - **2.3.** Integration and configuration of Firebase for storing translations, user inputs, and logs.
   - **2.4.** Configuration of the Unity AR Foundation toolkit to support AR functionalities on Android devices.
   - **2.5.** Implementation of a localized development environment to ensure app functionality without internet dependence.
3. **Development of Core Features**
   - **3.1. Text-to-Sign Translation:**

3.1.1. Developing a feature where users input a word, which the app translates into corresponding ASL gestures.

3.1.2. Using AR to display animated hand gestures corresponding to the translated word.

3.1.3. Implementing error handling for unsupported or unrecognized words.

3.2. Augmented Reality Hand Gesture Output:

3.2.1. Utilizing Unity's AR capabilities to render dynamic, accurate hand gestures in AR space.

3.2.2. Configuring the AR interface for optimal interaction with minimal latency.

3.2.3. Testing and fine-tuning AR animations for realism and clarity.

4. **System Testing**
5. **Deployment**
6. **System Troubleshooting and Maintenance**

3.5 Evaluation and Testing

To evaluate the effectiveness, reliability, and user-friendliness of KamayAR, a series of structured tests will be conducted. These evaluations aim to confirm that the application meets its objectives of providing accurate sign language recognition, seamless text-to-gesture translation, and overall ease of use for both deaf/mute and hearing users. The testing process will encompass three main components: Functional/Technical Testing, Performance Testing, and User Testing based on the Technology Acceptance Model (TAM).

1. **Functional/Technical Testing**

Functional testing will verify that KamayAR's core features work as intended across its primary modules. This includes ensuring accurate sign language gesture recognition, correct mapping of English text to corresponding ASL gestures, and proper AR overlay of 3D gesture models. Key areas for verification include the stability of the gesture capture process, responsiveness of the translation engine, and the correctness of outputs in both text-to-gesture and gesture-to-text modes.

Technical testing will also explore the integration of essential functionalities, such as camera input and AR rendering through the Unity platform. During this phase, potential issues such as crashes, inaccuracies in gesture recognition, or alignment problems in AR visualization will be documented. Test scenarios will involve translating commonly used English phrases, as well as capturing a range of ASL gestures under various conditions to ensure that all features operate as expected.

2. **Performance Testing**

Performance testing will measure the speed, efficiency, and resource usage of KamayAR. Metrics will include the time it takes to detect and analyze gestures, generate AR-based outputs, and transition between application screens. This stage will also assess the system's handling of different smartphone hardware specifications, focusing on processing load and memory consumption, particularly in environments with lower lighting or background noise.

Because KamayAR is intended to function effectively in diverse real-world settings, the ability to operate under limited connectivity or offline scenarios will be evaluated. Stress testing will further simulate high-frequency usage—for instance, rapid successions of gesture captures and text translations—to determine the application’s robustness. This helps ensure that the app remains stable and responsive even under demanding conditions.

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