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An IoT–AR Framework for Enhancing Interoperability for People with Disabilities

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ABSTRACT

Advanced technologies continue to accelerate, particularly in the fields of the Internet of Things (IoT) and Augmented Reality (AR), which have demonstrated significant potential in assistive technologies. Globally, approximately 15% of the population lives with some form of disability, highlighting the urgent need for intelligent and accessible solutions. In Saudi Arabia, recent statistical reports indicate that 5.9% of Saudi citizens experience at least one mild physical difficulty, while 1.8% of the total population lives with at least one disability, with mobility and visual impairments among the most prevalent categories. To better understand real-world challenges, in 2024, an interview was conducted with a PhD holder with visual impairment, focusing on daily mobility challenges, current assistive technologies, and desired improvements. The findings revealed critical limitations in accuracy, response time, usability, and system integration. This paper analyzes existing AR–IoT assistive solutions and identifies key challenges, particularly latency, accuracy, and interoperability between heterogeneous devices and platforms. Current systems often require multiple software applications and hardware components, increasing complexity and cost. Therefore, this research proposes enhancing interoperability between AR and IoT technologies through a unified compatibility framework aimed at reducing system complexity, improving efficiency, and increasing accessibility for individuals with disabilities.

Keywords: *Internet of Things (IoT), Augmented Reality (AR), Assistive Technologies, Interoperability, People with Disabilities, Human–Computer Interaction, Saudi Arabia.*

1. INTRODUCTION

Human–Computer Interaction (HCI) has expanded considerably in recent years due to rapid technological improvements, especially with the integration of Augmented Reality (AR) and the Internet of Things (IoT). These technologies have demonstrated significant potential in the creation of assistive systems that improve the quality of life and independence of people with disabilities. While AR offers user-friendly and interactive interfaces that can facilitate daily activities and navigation, IoT enables real-time data collection and smart environment control [1].

Even with these improvements, there are still a number of issues with current assistive technology. When implemented in the real world, many IoT-based solutions prioritize usability over capabilities. Additionally, there are new issues with system complexity, response time, heterogeneous device compatibility, and lack of interoperability when integrating AR with IoT. Because of this, people with disabilities still struggle to use these technologies efficiently and on their own [2].

Previous studies have explored various assistive solutions using AR and IoT technologies, such as smart navigation systems and real-time monitoring applications. However, these systems often rely on multiple hardware components and software platforms, leading to increased cost, reduced scalability, and limited interoperability. This highlights the need for more integrated and flexible solutions that can dynamically connect different technologies [1][2].

To better understand real-world challenges, an interview was conducted in 2024 with a PhD holder with visual impairment. The findings revealed key issues related to accuracy, response time, usability, and system integration [3]. These findings highlight the importance of developing systems that are not only functional but also interoperable and more efficient.

Therefore, this paper reviews existing systems, highlights interoperability challenges, and suggests a conceptual framework. The paper is organized as follows: Section 2 presents the literature review and discusses existing systems and their limitations. Section 3 describes the proposed methodology for achieving interoperability. Section 4 concludes the paper and outlines future research directions.

2. LITERATURE REVIEW

This section examines the body of research on assistive technologies for individuals with disabilities, concentrating on three primary areas: Internet of Things (IoT)-based systems, Augmented Reality (AR)-based systems, and integrated IoT–AR systems. IoT frameworks and applications are examined first, then AR assistive technologies, and lastly studies that integrate both technologies. The examination of current systems reveals important shortcomings, which create the research gap that this work seeks to fill.

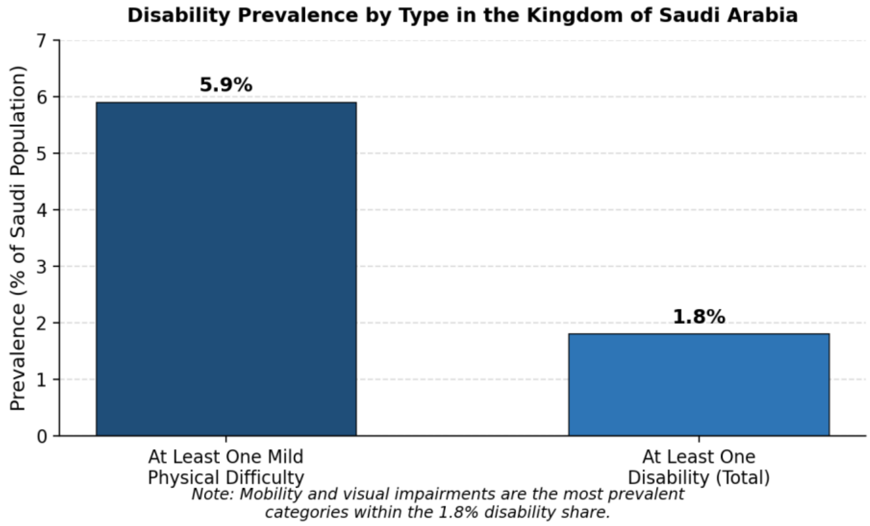

Fig. 1: Disability Prevalence by Type in the Kingdom of Saudi Arabia

2.1 IoT-Based Assistive Systems
To improve the lives of people with disabilities, a comprehensive IoT framework has been developed. There are three architectural levels in the framework.

2.1.1 Hardware
This level consists of body micro- and nano-sensors that are incorporated into wearable technology like smart glasses, canes, and gloves [10]. RFID-based assistive technology for navigation and item recognition is also included [12]. RFID tags on sidewalks and landmarks offer tactile or auditory direction clues to those who are blind or visually challenged. Additionally, the level includes motion sensors for those with physical disabilities, vibrating sensors for the deaf, and robotic devices with actuators for mobility assistance [2].

2.1.2 Connectivity
Using communication protocols including Wi-Fi, Bluetooth, ZigBee, and LPWANs, this level controls data delivery. It manages mesh networking, routing, forwarding, and security via authentication and encryption [2].

2.1.3 Software
Smart home automation, indoor navigation systems, interactive shopping support, and educational resources for children with disabilities are just a few of the user-centric solutions offered by this level [2][11]. Numerous application situations have been illustrated. An RFID-enabled smart cane that interacts with RFID tags on goods and floors to allow voice-guided navigation enables visually impaired people to shop independently in retail settings [2]. Smart home servers provide automatic shopping lists based on food inventories, while RFID chips on clothes allow automated laundry management [2]. Through interactive animations and movies, RFID-tagged toys assist deaf youngsters in learning sign language in educational settings [2].

2.2 AR-Based Assistive Systems
By superimposing digital data on the actual world, augmented reality (AR) has become a game-changing tool that helps people with disabilities [5]. AR systems address a variety of disabilities, such as visual, hearing, and movement impairments, by offering real-time aid and support depending on the user's individual needs [1].

2.2.1 Hardware
A variety of hardware components are used by AR assistance systems. These include wearable technology like smart gloves and haptic belts, smart glasses, smartphones, and head-mounted displays (HMDs). Cameras and sensors record the user's surroundings for real-time processing in navigation apps. Smartphones are the main hardware platform used to present visual signals for Parkinson's disease support [1].

2.2.2 Connectivity
For cloud-based services and real-time data processing, AR systems for people with disabilities frequently depend on wireless connectivity. AR devices may communicate with distant servers via Wi-Fi and cellular networks to perform activities like database access, picture recognition, and natural language processing. However, latency continues to be a major issue that impacts real-time performance [1][6].

2.2.3 Software
Software platforms like Unity, Vuforia, and ARKit are used to create AR apps. Convolutional neural networks (CNNs) and other machine learning and deep learning models are used for sign language translation, scene description, and object identification [7]. For instance, CNNs are used by Microsoft's Seeing AI program to identify items and provide auditory feedback that describes situations [8]. For visually challenged users, the ARIANNA+ system generates virtual navigation pathways using ARKit [1][9].

2.3 IoT–AR-Based Assistive Systems
Combining IoT and AR into a single system has been less explored, despite the fact that both technologies have been investigated independently for assistive applications. This integration may be expanded to a wider range of assistive applications beyond smart home management, even though it currently enables control of household appliances using AR interfaces connected to Wi-Fi-based microcontrollers.

2.3.1 Hardware
A 5V relay module controlled AC appliances, an ESP32 microcontroller served as the system's central processing unit, and a DHT11 sensor tracked humidity and ambient temperature. The ESP32 ran at a typical frequency of 160 MHz and included integrated Wi-Fi connection. Appliances were turned on and off by the relay module, which functioned as an electronically driven switch [4].

2.3.2 Connectivity
The ESP32 microcontroller and the Blynk cloud server communicated over Wi-Fi. By sending authentication tokens to the user's email, the Blynk application programming interface (API) made it possible to remotely operate appliances via the internet. The maximum ON time was 2.4 seconds at 3 meters, 2.7 seconds at 5 meters, 2.8 seconds at 7 meters, and 2.85 seconds at 10 meters. The transmission time was tested at various ranges. The transmission time went up to 2.9 seconds for ON and 2.8 seconds for OFF when there was a wall obstruction. Good network performance was indicated by the received signal strength indicator (RSSI), which was measured between -23 dBm and -25 dBm [4].

2.3.3 Software
Unity3D and the Vuforia software development kit (SDK) were used to create the augmented reality application. On picture targets, virtual buttons were made and positioned. Virtual buttons emerged when a user used the AR camera to scan an image target, giving them control over household equipment. The virtual button functionality was programmed using the C# scripting language, and the Blynk cloud platform was utilized to update the device status [4].

2.4 Limitations of Existing Systems
Even though IoT and AR technologies offer a lot of promise to help people with disabilities, a number of limitations have been noted in the cited literature.

2.4.1 IoT-Based Limitations
Given its comprehensiveness, the IoT architecture confronts a number of limitations. First, the varied and distinct requirements of people with various disabilities continue to make customization and personalization challenging. Second, many tasks still require human interaction since self-management skills like self-configuration, self-healing, self-optimization, and self-protection are still in their infancy. Third, a major technological difficulty continues to be compatibility across heterogeneous devices made by various vendors. Fourth, the sensitive data that IoT devices gather raises privacy and security issues. Fifth, battery-powered assistive technology raises questions about energy efficiency. Sixth, those from lower socioeconomic backgrounds have less access due to price [2].

2.4.2 AR-Based Limitations
AR assistance systems encounter a number of limitations as well. There is a lack of customization and flexibility to meet the demands of unique users. Real-time obstacle identification and reaction may be hampered by latency problems in image processing. Effective implementation of multimodal feedback integration (visual, aural, and tactile) is still challenging. For people with a variety of disabilities, interfaces must be made more accessible and usable. Particularly in complicated or dimly lit surroundings, object identification accuracy and dependability might result in dangerous circumstances. Large training datasets raise data privacy issues, and contextual awareness is frequently inadequate [1].

2.4.3 IoT–AR-Based Limitations
The home automation system that incorporated AR and IoT showed a number of technical limitations. The ON time approached 2.85 seconds at 10 meters and 2.9 seconds via a wall, indicating that transmission delay varied with distance and environmental barriers. Appliance control dependability was impacted by virtual button sensitivity. Due to the system's reliance on Wi-Fi signal strength, network variations might cause problems. Furthermore, the system was only evaluated in controlled situations and for a small number of devices [4].

2.5 Research Gap
Several research needs have been identified based on the examination of current IoT-based, AR-based, and integrated IoT–AR systems. First, even though IoT devices have strong sensing and data collecting capabilities, people with disabilities frequently find it difficult to utilize their user interfaces. Second, although AR systems provide interactive and user-friendly interfaces, they usually lack real-time environmental data from IoT sensors and depend on external processing. Third, the number of integrated IoT–AR systems is still small, and they are frequently created for particular use cases (such as home automation) without taking into account more general interoperability needs. Interoperability is a crucial issue that has not received enough attention among the limitations listed in previous sections. Due to variations in hardware designs, data formats, and communication protocols, current systems find it challenging to facilitate smooth connection between heterogeneous IoT devices and AR platforms. Increased system complexity, less scalability, greater costs, and restricted flexibility to a variety of user demands are all consequences of this lack of interoperability. Thus, by establishing a uniform structure for hardware, connection, and software, this review article aims to provide a conceptual IoT–AR architecture that handles the interoperability issue. The framework aims to improve accessibility, scalability, and usability for people with disabilities by facilitating the smooth integration of heterogeneous IoT devices with AR interfaces.

Table-1: Comparative Analysis of Existing Systems

Technology Category	Target Disability	Hardware / Software	Benefit
Visual	Blind / Low Vision	AR Glasses, RFID, Ultrasound	Real-time obstacle and path detection
Communication	Hearing / Mute	ML, AR Overlays, Sensors	Sign language translation and live captioning
Smart Home	Physical / Mobility	IoT Sensors, AR Dashboards	Unified control of home appliances via mobile
Motor Assistance	Parkinson's / Physical	AR Visual Cues (laser lines)	Improvement in gait and reduction in falls

3. PROPOSED FRAMEWORK
In order to improve assistive technologies for people with disabilities (PwDs), this research proposes a conceptual IoT–AR interoperability architecture based on the research needs noted in the previous section.

The framework's main objective is to provide smooth communication and integration between diverse IoT devices and AR systems, resolving significant issues including inadequate scalability, excessive latency, and lack of standards. The framework, which is divided into three primary levels, is structured similarly to current IoT designs but has been altered to facilitate AR integration.

3.1 Hardware

Describes the physical elements, such as AR display devices (smartphones, smart glasses, head-mounted displays), microcontrollers, actuators, and Internet of Things sensors.

3.2 Connectivity

Outlines cloud platforms (Blynk server) and communication protocols (MQTT, Wi-Fi, Bluetooth, HTTP APIs) to guarantee dependable data transfer between devices.

3.3 Software

Outlines AR development platforms (Unity, Vuforia), IoT control software, and middleware for data translation and interoperability. Because each level is uniform and modular, parts from many manufacturers can cooperate without the need for individual integration. Each level is explained in depth in the next subsections.

3.3.1 Hardware Level (Detailed)

IoT sensor devices, processing units, and AR display devices make up the three primary categories of the hardware level of the suggested structure. IoT Sensors and Actuators — depending on the application situation and disability, the framework supports a variety of sensors, according to the literature. These include temperature and humidity sensors (DHT11) for environmental monitoring [4], motion detection sensors (PIR) for presence detection [2], gas sensors (MQ2) for safety and emergency detection [2], moisture sensors (HL-69) for automated irrigation systems [2], RFID tags and readers for navigation, object identification, and smart home applications [12], and ultrasonic sensors for proximity alerts and obstacle detection [10]. Microcontrollers and Processing Units — to guarantee affordability and wireless connection, the architecture suggests using inexpensive microcontrollers with Wi-Fi capability. The ESP32, which runs at 160 MHz, has several GPIO ports for attaching sensors and actuators, and has built-in Wi-Fi and Bluetooth, is one of the suitable possibilities found in the literature [4]. The NodeMCU ESP8266 is a more affordable option for simple IoT applications [2]. Multiple AR display choices are supported by the framework in order to give an easy-to-use and interactive user experience [5][6][9]. These include head-mounted displays (HMDs) for immersive AR experiences [6], smart glasses for hands-free interaction in advanced use cases [5], and smartphones (Android/iOS) as the most accessible and reasonably priced alternative for AR applications [4][8].

3.3.2 Connectivity Level (Detailed)

Reliable, secure, and low-latency data flow between IoT devices, cloud platforms, and augmented reality applications is made possible by the connectivity level. The following communication protocols and architectures are suggested based on the examination of current systems [2][4]. IoT Communication Protocols — depending on the needs of the application, the framework offers a variety of protocols to guarantee compatibility across heterogeneous IoT devices. These include HTTP/HTTPS (REST APIs) for communication between IoT devices and cloud platforms like Blynk and Firebase [4], CoAP (Constrained Application Protocol) for resource-constrained IoT devices in low-power networks [2], and MQTT (Message Queuing Telemetry Transport), a lightweight publish-subscribe protocol perfect for IoT applications with limited bandwidth and power constraints [2]. Wireless Connectivity Technologies — to facilitate smooth device connectivity, the framework makes use of common wireless technologies. These include Bluetooth and Bluetooth Low Energy (BLE) for short-range communication between wearable sensors and mobile devices [2], ZigBee for mesh networking in smart home environments with multiple IoT devices [2], RFID (Radio Frequency Identification) for short-range object identification and indoor positioning [12], and Wi-Fi (2.4 GHz / 5 GHz) for high bandwidth real-time data transmission and AR content delivery [2][4]. Cloud Integration and APIs — the framework uses REST APIs to link IoT devices to cloud platforms in order to provide remote monitoring and control. Platforms found in the literature include Firebase, which offers real-time database services for syncing data between IoT devices and AR apps [2], and Blynk, which offers a dashboard for controlling microcontrollers and displaying sensor data over the internet [4]. The framework suggests utilizing edge computing to process data closer to the source, optimizing network configurations for minimal packet loss, and choosing suitable protocols based on real-time requirements in order to address the transmission latency issues found in current systems [6].

3.3.3 Software Level (Detailed)

The AR development environment, IoT control software, and middleware components that provide interoperability between the two technologies are all included in the software level of the suggested architecture.

The following software components are suggested. AR Development Platforms — the following AR development tools are supported by the framework in order to construct interactive and user-friendly interfaces for people with disabilities. Unity3D, a popular cross-platform game engine for creating augmented reality apps, allows for the development of virtual buttons, 3D object rendering, and interaction with AR SDKs [4]. Vuforia Engine is an augmented reality software development kit (SDK) that smoothly integrates with Unity3D and offers 3D object tracking, virtual button functionality, and picture target identification [4]. Native AR SDKs for smartphone-based apps, ARKit (iOS) and ARCore (Android), include functions including motion tracking, light estimation, and environmental comprehension [9]. IoT Control Software — uses local control scripts and cloud-based platforms to handle IoT devices and sensor data. With virtual pins, real-time data visualization, and device identification through API tokens, the Blynk Platform offers a mobile dashboard for online control of microcontrollers (ESP32, NodeMCU) [4]. With libraries for sensors (DHT11, MQ2, RFID) and communication protocols (Wi-Fi, MQTT) easily accessible, the Arduino IDE is used to write and upload C++ code to microcontrollers [2][4]. Real-time data synchronization between IoT devices and AR apps is made possible by Firebase Realtime Database, which supports low-latency updates [2]. Middleware for Interoperability — the framework suggests a middleware component that handles device discovery and authentication across heterogeneous platforms [7][8], standardizes data formats (JSON) for smooth communication between IoT devices and AR applications, and translates data between various communication protocols (e.g., MQTT to HTTP) [4].

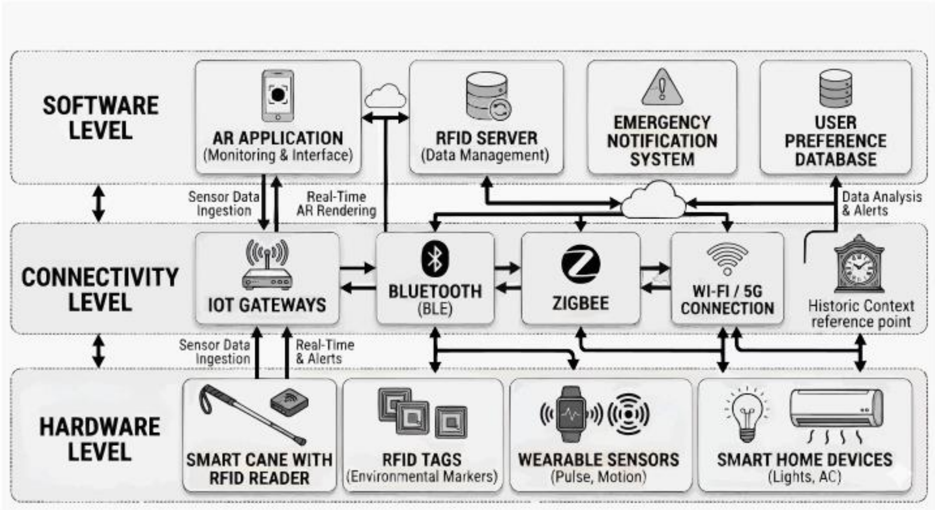

Fig. 2: Framework Levels Workflow

The main contribution of the suggested framework is to solve a major issue seen in current systems: the lack of interoperability between various IoT devices and AR platforms. The following mechanisms are used in the framework to overcome this challenge. Standardized Integrated Architecture — the framework is divided into three separate components (hardware, connectivity, and software), each of which functions independently via well-defined interfaces. Because of its modular architecture, parts from various manufacturers may be updated or changed without having an impact on the system as a whole. Middleware for Protocol Translation — the middleware component serves as a conduit between AR applications and IoT devices. It transforms data formats into a common JSON structure and translates data across various communication protocols (such as MQTT to HTTP). This guarantees that sensor data from any IoT device, independent of its native protocol, may be requested and received by AR apps. API Abstraction Levels — device-specific implementation specifics are concealed by the framework's uniform REST APIs. Without having to comprehend the underlying hardware or communication protocols, AR developers may communicate with IoT devices using straightforward HTTP queries. This speeds up the development of usable AR interfaces and lowers development complexity. Scalability and Extensibility — the framework may grow from a single IoT device to hundreds of devices without any changes thanks to its modular architecture. Without altering the AR application or other system elements, new device types or communication protocols may be added by just expanding the middleware. The suggested framework greatly increases interoperability, decreases system complexity, lowers development costs, and improves the general user experience for people with disabilities by putting these processes into practice.

4. CONCLUSION

This review paper examined existing assistive technologies for individuals with disabilities, focusing on three main areas: Internet of Things (IoT)-based systems, Augmented Reality (AR)-based systems, and integrated IoT–AR systems. The paper finds that the lack of interoperability between various IoT devices and AR platforms is a significant issue found in all solutions under consideration. As a result, the system becomes more complicated, less scalable, more expensive, and less able to adjust to different user demands. Significant obstacles were inadequate customization possibilities, transmission delay, and reliance on Wi-Fi signal strength [1][2][4]. In order to close the interoperability gap, this paper suggested a conceptual three-level structure (hardware, connectivity, and software) with a middleware component. To facilitate smooth integration between IoT devices and AR apps, the framework standardizes data formats, communication protocols, and APIs. Future research should concentrate on putting the suggested framework into practice and testing it with actual users, including people with all kinds of disabilities. Furthermore, investigating 5G networks and edge computing may help lower latency and enhance real-time performance. Lastly, the results would be strengthened by doing a comprehensive meta-analysis and adding more papers to the review.

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