ADVANCING ELECTRONIC HEALTHCARE IN AMBIENT ASSISTIVE LIVING UTILIZING INTELLIGENT MOBILE SYSTEMS

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By

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Dedicated to my family.

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Abstract

The continuously arising demand for advanced healthcare services puts significant pressure on current solutions, especially in the field of ambient assisted living. Such solutions include traditional systems which often incorporate static, expensive and not easy-to-use hardware. Remote patient monitoring, rehabilitation, physical activity motivation, navigation and accessibility are key scientific problems that the existing healthcare landscape tries to address using the mentioned conventional methods.

The latest technological advancements provide increased computational capabilities in even smaller devices, more lasting batteries and faster interconnectivity. In combination with the continuously evolving sensors (cameras, gyroscopes, accelerometers), mobile devices offer a set of data which can be efficiently utilized to cover various scenarios. As a result of these innovations, demanding Machine Learning (ML) algorithms are now capable of being executed in the palm of the user hands. Hence, tasks such as Computer Vision (CV), a subfield of Artificial Intelligence (AI) can be efficiently used in mobile devices with applications like Augmented Reality (AR) offering overlay of computer-generated content in the real world. In addition, Human-Machine Interaction plays a pivotal role in user engagement as systems with such advanced principles are proven to offer satisfactory experiences for the users.

This dissertation aims to address the aforementioned problem of advancing ambient assisted living by utilizing intelligent mobile systems such as mobile phones and smart watches. This thesis divides this goal into research questions including the feasibility of commodity devices to achieve the thesis goal, the importance of Human-Computer Interaction principles in healthcare, the integration of AR, IoT and Sensors technologies for remote patient monitoring, the increase in accessibility via intelligent handheld solutions, the location-aware possibilities to increase quality of life and medical education. Therefore, novel solutions are introduced

along with their results which highlight a direction towards a more pervasive healthcare landscape. These solutions include mobile patient monitoring systems which utilize gamification techniques, AR and IoT to motivate users to increase their physical activity indoors, to visit pocket parks and to utilize onboard motion sensors to monitor their gait asymmetries. Moreover, intelligent AR algorithms are used to achieve obstacle avoidance for the visually impaired and increase accessibility in exhibition areas. Handheld location-awareness is examined in the field of indoor localization, providing solutions to achieve indoor navigation without the need of additional hardware, incorporated by ML, and to facilitate better crowd management in museum scenarios. Finally, the combination of AR is combined with CV in commodity mobile devices to create a medicine box identification and compound visualization system, as a proof-of-concept prototype of a medical education assistant.

Overall, this thesis highlights that commodity devices, which have the benefits of cost and hardware elimination, can indeed facilitate an advanced ambient assisted living. Intelligent systems running on these devices are getting advantage of the onboard hardware and the edge to introduce novel proof-of-concept solutions and propose a direction towards accessible, personalized and cost-effective healthcare.

1 Introduction

Healthcare systems worldwide are facing unprecedented challenges, driven by increasing demand, limited resources, and the growing complexity of medical services. At the same time, rapid advances in digital technologies are reshaping the way care can be delivered, monitored, and optimized. Against this backdrop, this thesis explores the intersection of healthcare needs and emerging intelligent methods, with the aim of identifying how such innovations can help alleviate systemic pressures and improve patient outcomes.

1.1 Scope

The scope of this thesis is framed by the mounting pressures on healthcare delivery, the potential of intelligent technologies to address these issues and the motivation to apply such advancements in practice. By examining these elements, the work establishes both the relevance of the research and the rationale for pursuing technology-driven solutions in modern healthcare.

1.1.1 Current status in healthcare

The modern healthcare landscape is experiencing significant pressure [1] with traditional patient monitoring practices and healthcare systems affected by this shift. Various factors play a major role in this situation with the most major one being the continuous age of the population [2]. This continuous increase in human lifespan is undoubtedly of tremendous value and confirms the importance of scientific advancement. However, it also emphasizes the need for innovation and the development of more flexible and intelligent healthcare solutions. In addition, as the population is aging, chronic diseases are multiplying and even scenarios of Multimorbidity (the co-existence of two or more chronic conditions) are no longer rare phenomenon [3], confronting the leading causes of deaths and disabilities. For instance, in the US, such diseases are a denominator of the nation's healthcare costs [4], a fact that highlights the need for research in this field additionally. This economic burden affects patients both directly and indirectly with increases in healthcare expenditures and loss in possible economic productivity. Hence, healthcare systems in the western world are facing extraordinary pressure and, especially for the elderly, often instantly occupy a portion of their income. Eventually, in some cases, this situation lurks the risk of poverty [5]. The quantitative increase in numbers highlights the need for more proactive healthcare systems and procedures. A transition to more patient-centric healthcare models and continuous health monitoring procedures can play a key role in preventing such conditions and increasing quality of life.

1.1.2 Intelligent technologies in eHealth

This shift is only possible through the integration of advanced technologies which offer innovative combinations of state-of-the-art hardware and intelligent software. The utilization of such technological trends (like Machine Learning, Computer Vision and other algorithms and methodologies) to process data and make intelligent decisions define the era of eHealth Intelligence (eHI). eHI introduces adaptive mechanisms that enable intelligent behavior in complex and changing environments [6]. In this context, the challenge of how eHI approaches can facilitate remote patient monitoring and improving the quality of medical services is proposed.

The latest advancements in microprocessors, sensors and batteries in cooperation with software innovations have the advantage of executing even heavier computational tasks while maintaining a low energy impact [7]. This allows the execution of innovative algorithms and modern techniques into mobile and commodity devices, capitalizing their processing power towards offering handheld and personalized experiences.

A heavy yet applicable Machine Learning (ML) task supported by commodity mobile devices is Computer Vision (CV) and its subsidiary, Augmented Reality (AR), confronting the Mobile Augmented Reality (MAR) term [8]. AR technology utilizes the mobile device camera and Inertial Measurement Unit (IMU) sensor and refers to a real-time direct or indirect view of a physical real-world environment that has been enhanced/augmented by adding virtual computer-generated information to it [9]. The immersive experiences that arise from utilizing such technology offer suitable land for research in the fields of user physical and mental activity increase, user engagement, education and navigation. Additionally, AR can be effectively integrated with structured training and monitoring approaches, such as Gamification, to improve behavioral outcomes [10]. More advanced techniques may utilize ML with AR to facilitate better real-world understanding or to locate key information using ML and then visualize it through AR. The mentioned combinations of techniques indicate possibilities for research and innovation, all in the scope of proposing intelligent and non-resource hungry systems for user supporting.

Mobile commodity devices offer various sensors that can be used to facilitate intelligent computational tasks. These devices include both mobile phones and wearable IoT devices, such as smartwatches. The sensor data that can be retrieved vary from motion data (accelerations and rotation rates) to health data (heart rate) and activity data (steps and distance), highlighting the possibilities of a multi-modal approach. The idea of having such valuable information in a device that is always with or attached to the user generates opportunities.

1.1.3 Motivation

The motivation of this thesis is to propose solutions for the aforementioned problems of healthcare environments by utilizing intelligent technologies. These technologies aim at improving healthcare in various aspects via user-centric approaches, without additional hardware interventions and without additional cost. The research goal lies on how data produced by commodity hardware can be intelligently utilized into computational systems for remote supporting and improving quality of healthcare. This highlights the need to collect rich and multi-modal data like physical activity, gait patterns or location information using accessible and cost-effective mobile devices.

1.2 Research questions

The research questions of this thesis aim at addressing the needs of Remote Patient Monitoring and improving the quality of medical systems via eHI approaches.

1.2.1 Question 1: Can commodity mobile devices facilitate efficient assistive living?

Assistive Living is a highly researched field with proposed applications and approaches varying from using wearable sensors to ambient equipment, to enhance Remote Patient Monitoring (RPM) [11]. Existing systems are helping the users in their rehabilitation procedures and are increasing the quality of life of chronic patients. However, they include major drawbacks which act negatively on motivating users to use them. A primary disadvantage is the requirement of sophisticated hardware which mostly is not const effective. The reliance on hardware increases the complexity of the use of such solutions which may also be static or present difficulties in relocations. These user inconveniences result in a lack of engagement and, eventually, lack of adherence and loss of data collection. Key requirement of the proposed studies is the need of hardware and cost elimination, introducing solutions which increase accessibility, ease of use and user engagement.

1.2.2 Question 2: Is the adoption of advanced Human-Computer Interaction techniques improving healthcare services?

It will be assessed if the utilization of advanced Human-Computer Interaction (HCI) techniques in combination with portable hardware (commodity devices, IoT wearables and others) and edge technologies (ML, CV, AR and others) can improve eHI systems effectiveness. The study will examine whether robust, mobile, and customizable systems can enhance patient motivation for physical and cognitive activity, facilitate rehabilitation processes, and improve accessibility across diverse settings.

1.2.3 Question 3: How can AR, IoT and Sensors technologies engage users for Remote Patient Monitoring?

The research questions that arise in this context lie on how eHI systems can facilitate a more comprehensive and effective RPM. This thesis will assess the utilization of commodity devices for increasing human activity and cognition [12] using AR, IoT [13] and Gamification practices [14]. Moreover, the integration of indoor gamified AR solutions into an end-to-end remote monitoring system will be assessed when applied as a patient's healthcare plan. Commodity devices may also be combined with outdoor activity increasing health and wellness. Finally, valuable data from commodity device IMU sensors can be also assessed on whether they can monitor kinetic diseases as reliable as dedicated sensors.

1.2.4 Question 4: How can AR and CV enhance medical education?

The continuously evolving mobile CV technologies have resulted in very efficient solutions which perform on-device inference [15]. While CV provides the capabilities of identifying objects in a camera feed, this thesis examines the possibilities of combining CV object identification with the advanced visualization and user engagement benefits of AR. These benefits will be examined in the field of Education.

1.2.5 Question 5: Is it feasible to create intelligent location-aware assistive environments?

Simultaneous Localization and Mapping (SLAM), which is the foundation of AR, addresses the problem of localization and mapping when a prior map of the workspace is not accessible [16]. It utilizes camera feed and data from IMU sensors and can be executed in commodity mobile devices. The research questions that arise from delving into this technology are found on the applicability of SLAM as an indoor navigation solution. The eHI extension of assisting SLAM-based navigation with ML for better indoor positioning can also be investigated. Finally, intelligent procedures which combine SLAM with gamification can be studied towards crowd management.

1.2.6 Question 6: How mobile solutions can increase accessibility for the impaired?

In the scope of increasing the quality of life of the disabled, AR may be used as world-understanding mechanism. It is going to be examined if it can increase accessibility of the impaired by identifying objects and locations, in multi-tenant platform approaches. Moreover, it will be investigated on whether intelligent solutions can be applied to the scenario of obstacle detection. SLAM and advanced depth estimation data processing are going to be addressed against supporting the visually impaired using commodity device solutions.

1.3 Thesis Contribution

In this thesis, the goal is to study how intelligent mobile systems can be capitalized to facilitate assisted living. While studies in these fields propose advanced and efficient solutions, this research focuses on optimizing existing hardware via intelligent software. The contribution of this work is divided into four pillars:

1.3.1 Engaging users for increasing their physical and mental activity and RPM using AR, IoT and IMU technologies

This pillar focuses on utilizing AR, IoT, and IMU sensor technologies to develop systems that engage users in physical and cognitive activities while enabling Remote Patient Monitoring. The research includes the design and implementation of AR-based exergames that motivate users to increase their physical activity through gamification. These exergames integrate IoT wearables, such as smartwatches, to monitor real-time biometrics like heart rate, steps, and hand trembling, which are transmitted to healthcare professionals via a cloud platform. Additionally, the thesis extends these concepts to outdoor environments, such as Nature-Based Solutions (NBS), where AR, gamification, and IoT are combined to encourage users to engage with green spaces and adopt healthier lifestyles. Furthermore, the thesis introduces a novel approach for detecting gait asymmetry using IMU sensors in commodity devices, offering an accessible and cost-effective solution for patients undergoing rehabilitation. This pillar answers to Questions 1, 2, 3 and 5.

1.3.2 Assisting the impaired through handheld SLAM-based solutions

This pillar addresses the challenges faced by visually impaired individuals through the development of handheld SLAM-based assistive systems. The research introduces a novel obstacle detection and navigation system that leverages SLAM and depth estimation capabilities of commodity mobile devices. The system identifies obstacles and downhill cliffs in real-time and provides users with haptic and audio feedback to assist navigation. A unique algorithm for depth image segmentation and obstacle classification is proposed, enabling accurate detection without the need for specialized hardware. Additionally, this pillar explores the use of AR-based exhibit recognition systems to enhance accessibility in museums and exhibitions, allowing visually or hearing-impaired individuals to interact with exhibits using only their mobile devices. This pillar answers to Questions 1, 2, 5 and 6.

1.3.3 Introducing location-aware mobile intelligent systems for navigation and localization

This pillar focuses on intelligent location-aware systems that utilize AR and SLAM technologies for indoor navigation and localization. A state-of-the-art AR indoor navigation system is developed, employing novel routing algorithms and a multi-floor navigation model to guide users seamlessly through complex environments, such as hospitals and public spaces. The thesis further extends this solution by introducing Continuous Machine Learning (CML) techniques to enhance the adaptability of the navigation system. This approach allows the system to learn from changes in the environment, such as object relocations, ensuring robustness and scalability. The research also explores crowd management in exhibition areas by combining AR navigation and gamification, enabling real-time monitoring of visitor flow and improving user experiences in crowded settings. This pillar answers to Questions 1, 2 and 5.

1.3.4 Facilitating medical education through AR and CV

This pillar highlights the use of AR and Computer Vision (CV) to enhance education and knowledge dissemination in healthcare. A mobile application is developed to recognize drug packaging through CV algorithms and visualize the molecular compounds of pharmaceutical substances using AR. This system connects to external chemical databases, such as PubChem, to retrieve detailed information about drugs, providing an interactive and immersive educational tool for healthcare professionals and students. The research demonstrates how AR and CV can be effectively combined to create engaging, user-centered applications that enhance medical training and knowledge retention. This pillar answers to Questions 1, 2 and 4.

These four pillars collectively address critical challenges in healthcare delivery and assistive living, demonstrating the potential of eHealth intelligence and commodity mobile devices to transform healthcare systems. By offering cost-effective, scalable, and user-friendly solutions, this thesis contributes to advancing the state of the art in intelligent healthcare technologies and Ambient Assistive Living environments.

1.4 Thesis Structure

The thesis is structured in six main sections as follows: 1. Introduction, 2. Related Work and Background Information, 3. Methodology, 4. Results, 5. Discussion and 6. Conclusions.

The “Introduction” section defines the broader scope of the thesis by presenting the current state of healthcare systems, emphasizing the challenges posed by increasing demands, aging populations, and the growing prevalence of chronic conditions. It highlights the limitations of traditional healthcare solutions and introduces the potential of cutting-edge computational technologies—such as Augmented Reality (AR), Computer Vision (CV), Internet of Things (IoT), and Simultaneous Localization and Mapping (SLAM)—to offer innovative, user-centric, and cost-effective alternatives. The section establishes the motivation for the research, outlines the research questions, and provides an overview of the contributions made in the context of four core pillars: engaging users for physical and mental activity and Remote Patient Monitoring (RPM), assisting the impaired through SLAM-based solutions, introducing intelligent location-aware healthcare environments, and facilitating medical education through AR and CV.

The second section, entitled “Related Work and Background Information” firmly serves two purposes: to present the related literature of each implementation of the thesis and to introduce the reader to the knowledge base that is required to understand the rest of the dissertation. Related literature explains shortly what are the relevant studies that either serve the same purpose or utilize the same technologies of each proposed solution, identifying the scientific gaps and open challenges. Background information provides the reader with textbook material on the terminology that is used across the other sections of the thesis. A vital subsection the reader should refer to if any misinformation occurs.

The "Methodology" section outlines the design, architecture, and implementation of the proposed solutions. Each of the four pillars is explored in detail, with dedicated subsections describing the system requirements, innovative algorithms, data models, and integration of hardware and software components. The section emphasizes the scalability, modularity, and accessibility of the proposed systems, ensuring their applicability in real-world healthcare scenarios.

The "Results" section presents the outcomes of the research, focusing on the real-world applicability and performance of the proposed systems. Quantitative metrics such as system efficiency, accuracy, and user interaction rates are complemented by qualitative insights from user testing and feedback. Each solution is evaluated against its intended objectives, demonstrating its feasibility, scalability, and impact on healthcare delivery and user engagement.

The "Discussion" section explains why the proposed designs, architectures, implementation along with the results are novel and within the thesis scope. The thesis contribution is summarized which highlights the novelties of this study compared to the thesis goals. The presented study is compared to other works, indicating the literature gap fulfillment and the innovation of the thesis. Additionally, the lessons that were learned through the thesis process are stated along with the presented difficulties and the methods to overcome them. A mention of the general context of the studied solutions is performed highlighting their application and effectiveness. Finally, the section proposes extensions for further research in the fields of interest. Overall, this section covers the research scopes of the study and answers on why the methods presented, applications and results can define a doctorate thesis.

Finally, the work concludes with a summary of the research conducted and the corresponding outcomes, expanding the applications of mobile intelligent systems towards Remote Patient Monitoring and improving the quality of Health Delivery Systems.

2 Related Work and Background Information

This section presents an extensive overview of related literature. The focus is placed on how the presented technologies have been utilized to address challenges in the thesis domains and how they can be adapted and extended to meet the specific needs of electronic healthcare and Ambient Assistive Living environments. Additionally, it introduces the theoretical and technical foundations necessary to understand the proposed approaches, ensuring a comprehensive and informed perspective for the reader. This includes definitions of sophisticated terminology and explanations of intelligent algorithms.

2.1 Literature review

The Literature review is divided into works that serve the purpose of the pillars, as follows:

1. **Engaging users for increasing their physical and mental activity and RPM using AR, IoT and IMU technologies**
2. **Assisting the impaired through handheld SLAM-based solutions**
3. **Introducing location-aware mobile intelligent systems for navigation and localization**
4. **Facilitating medical education through AR and CV**

The following subsections explore the state of the art for each of the four research pillars, focusing on technologies which are central to this thesis. Each subsection highlights how these technologies have been successfully applied in other fields and identifies the scientific gaps in their application to healthcare and assistive living. By addressing these gaps, the thesis aims to propose novel, intelligent solutions that leverage these technologies to improve healthcare delivery, accessibility, and user engagement in Ambient Assistive Living environments.

2.1.1 Engaging users for increasing their physical and mental activity and RPM using AR, IoT and IMU technologies

The following subsections present the current state of the art regarding AR, IoT and sensors for remotely supporting and monitoring patients in the scenarios of physical activity motivation and navigation.

2.1.1.1 Gamified AR and IoT platforms for remotely assessing physical activity

AR technology refers to a real-time direct or indirect view of a physical real-world environment that has been enhanced/augmented by adding virtual computer-generated information to it. In the video games industry, AR solutions [17] are quite common nowadays, and typically gameplay scenarios impel players to increase their physical activity. Such games are called exergames and encourage the players to perform exercises and movements that, under other conditions, they would not perform [18] [19] [20]. To achieve the goals of such serious games, the use of gamification techniques is mandatory [21], and through the different goals of a game, players are required to perform physical and mental challenges to improve, mainly in a mid- to long-term time frames, their physical conditions and lifestyles.

Physical activity interventions using video games have been the core subjects of studies, especially in recent years and demonstrate positive results [22] [23], including children and elders [24]. Similar approaches implement human motion analysis methodologies and tools for exergame development, which are based on computer vision, deep learning technologies, and edge computing technologies [25]. Active video games in classrooms motivate students to conduct physical exercise [26], resulting in healthier lifestyles. Exergames can promote physical activity in the scope of personalized health [27] and are defined as a combination of exertion and video games [28]. Moreover, for elderly people, they aim at continuously mobilizing and encouraging them to perform exercises or movements that they otherwise would not do [29], and to follow a specific plan of activities and challenges in the context of their care plans. During COVID-19 distancing conditions, indoor virtual reality exergames show positive results in increasing the physical states of users while maintaining high user satisfaction [30]. In a telerehabilitation exergame platform, which combines mobile devices and remote sensors, stroke patients showed signs of balance improvement [31].

One of the fundamental techniques of the serious game design is gamification. This goal, in the research areas related to this work, is mainly to increase physical and cognitive activities. In addition, with the combination of virtual and augmented reality technologies, user activities can be increased as part of healthcare solutions [32]. It should be noted that despite virtual reality applications showing positive results, they still require additional, and in most cases, expensive hardware [33] [34] [35]. Another disadvantage of VR is the absence of representations of the user’s body, highlighted by an exergame aimed at reducing risk fall for the elderly [36]. This game promotes AR over VR due to the increased sense of body presence AR provides and the advantage of operating on low-cost commodity hardware.

Research implementations based on the Microsoft Kinect system, a hardware extension to the Microsoft XBOX using RGB and depth cameras, show that such platforms can be highly efficient in medical aspects and support exergames [37] [38] [39]. Nintendo Wii sports is also a platform that has similar, positive results [40]. There are AR examples that increase the motivation and monitoring of users while exercising and help them maintain their physical conditions [41]. Pokemon Go is a widely used AR game that motivates the user to go out and search for dropped virtual objects [42] [43]. Additional solutions refer to mobile AR exergame applications that use virtual objects and spatial audio to encourage player movement [44]; some focus on specific user groups, e.g., motivating children to move by finding and defusing virtual calorie bombs in a real-world environment [45]. Applications using the Google ARCore framework can be found in the context of in-house navigation systems [46] [47] and focus on the aspects of improving the users' quality of life.

The use of IoT wearable devices, which can monitor the users' physical state [48], is also beneficial to achieve the goals of these games. IoT wearables in medicine are small and flexible electronic devices that can measure physical status and record physiological parameters of the user [49]. Smart wearables are used for fitness [50] tracking, recommendations, and guidance, and can record physical activity aspects [51] along with other measurements, such as heart rate or blood oxygen saturation. Such devices are the core hardware components that realize quantified-self concepts, which refers to the engagement of individuals to self-track any kind of biological or physical information [52]. Rehabilitation data recorded by IoT devices can be stored in the cloud. Related research in the concept of sensor data analysis [53] indicates that these data can be saved, queried efficiently, and accessed by web interfaces.

Combinations of AR and IoT can be found in cases of communication between mobile devices and static infrastructure. Such examples can be found in agriculture, where they facilitate in improving precision farming, especially for indoor planting [54]. In smart cities, IoT sensors provide location-based information presented in the user interfaces, as virtual objects through their mobile phones. This information can vary from transportation announcements [55] to general context defined by dynamically placed markers [56]. Real-time environmental data are demonstrated by AR mobile applications providing engaging ways of IoT sensor data visualization [57].

Studies that indicate a gap between AR and IoT in the healthcare context discuss architecture and technologies that can be used to perform such integration [58]. Intelligent assistive systems, combining Internet of Things, augmented reality, and adaptive fuzzy decision-making methods help users complete their daily life activities [59]. IoT solutions using the "Simblee" platform for health data monitoring aim to improve patient engagement during physical rehabilitation with the use of AR [60] for iOS devices.

Although studies show examples of combining AR exergames with IoT, the linking of these two as a prototype exergame for mobile commodity devices with hardware independence, remote configuration, doctor web interface, cloud functionality and IoT health monitoring, is missing in the literature.

2.1.1.2 Cloud-Enabled Gamification to Enhance Participation in Nature-Based Solutions

Urban Planning can be a high complexity process based on the location, the size of the city and the natural characteristics of each area. The urban planning requires a deep analysis of several factors, such as the real estate prices, the transportation and the local services, the micro-climate of the city as well as public health and citizens' well-being. During the last decades, the scientific community suggests the inclusion of Nature-Based Solutions (NBS) and Blue-Green Spaces in urban environmental planning. The aim is to redesign and develop healthier cities by following the Healthy Urban Planning (HUP) approach as this has been proposed by WHO [61] [62]. Cities from all over the globe seem to understand the necessity and the value of the HUP to provide a resilient environment to the citizens [63] [64]. According to relative studies, novel urban design strategies can significantly affect the citizens' outdoors physical activity and the cities response to the climate change effects [65] [66]. Recent studies propose solutions to increase the citizens' safety and engagement in visiting areas with NBS. These solutions include several sensors and technologies, aiming to provide to citizens' better experiences in a healthy urban environment [67] [68] [69]. In addition, during the COVID-19 pandemic, the need for a revision on the urban planning methods and approaches has been revealed [70].

Adopting a lifestyle of prosperity by its individuals is vital in a modern society. For this way, eHealth systems that consider changing their users' habits to healthier ones, have to combine easy-to-implement and pleasant-to-use strategies to motivate them for achieving specific goals. The use of game mechanics is a technique known as gamification and is adopted as strategy for a variety of purposes in different contexts [71] [72] [73] [74]. Additionally, as it is a widely used and approved mechanism, it can be used in the concept of intelligent guiding in such apps and improve the user's experience. Systems that attempt to highly motivate their users must implement elements that are deeply integrated in the users' interface while in parallel, the system must support these game mechanics and the respective elements by design so that it can be effective. Additionally, applications exploiting the wearable devices and the related technologies include, among others, health monitoring, activity recognition, tracking and localization, safety, and are the perfect candidates for using the gamification elements to enhance the user experience [75].

The most common and historically the traditional form of a gamification approach is the Points - Badges – Leaderboards [76]. Points are used as in-app credits to "unlock" other features, while the Badges are awards that a user wins every time specific actions or quests are accomplished. Leaderboards are visual features which enable users to get informed where they rank in relation to other users. Hanranths 2016 et al. [77] describes a framework based on game elements in learning environments to engage user's motivation. Ilhan et al. [78] analyzed the gamification methods used in fitness apps such as Samsung Health, Garmin Connect, and Fitbit to motivate their users to adopt more healthy lifestyle habits. Game mechanics like Goals, Points, Levels, Badges, Leaderboards are found to change the user's behavior by motivating and making the activity enjoyable. More specifically, the Leaderboards motivate the user to become better than other users are, while Badges are pleasurable features for users who enjoy getting rewards after a goal completion. Additionally, by using wearables, studies have shown that it may engage the users in a training program on a regular basis which can lead to significant health improvements [79].

AR technology is the ability of the seamlessly integration of already existing environments enriched with computer generated visualized information [80]. User adoption of AR shows high rates in the consumer context and thus offers a comprehensive user environment [81]. Integration of AR with GIS services evaluates the parameters of different features such as performance, usability, effectiveness and satisfaction [82]. MAR is applicable in campus navigation systems [83] and in real-time location-based advertising platforms [84]. Furthermore, AR shows positive outcome in the Health and Fitness field.

A combination of cloud-based AR content used as gamification elements for motivating citizens to visit a NBS solution serves towards the thesis goals and defines a gap in the literature.

2.1.1.3 Remote gait asymmetry detection

Common stroke gait impairments are characterized by alterations in the stance and/or swing phases of the paretic limb, resulting in slow walking, low cadence, decreased stride length, increased spatiotemporal asymmetry, by increased step and stride variability [85]. Creating strategies that help target gait impairments, increase mobility and community participation are recognized as one of the highest priorities after surviving a stroke [86] [87]. Accurate assessment of gait kinematics is helpful in predicting the outcome and degree of improvement in functional abilities achievable post-stroke, and it is useful in assessing patient's main gait deficits, designing rehabilitation programs, and monitoring improvements [88].

Traditional gait analysis methods require specialized equipment, professional expertise and controlled laboratory environments, limiting their accessibility and practicality in everyday clinical settings [89]. Evaluation of gait features during the assessment, e.g., asymmetry and variability, are not routinely recorded. These features may provide additional insights into the individual walking dysfunctions after stroke, leading to improved clinical decision making [90]. It remains difficult for stroke patients and clinicians to obtain reliable gait assessment data easily, especially from an in-home setting [91]. It has been demonstrated that portable devices, such as IMUs, can objectively measure gait and detect changes in gait phases during rehabilitation [92]. Smartphones, equipped with accelerometers and gyroscopes, offer a portable, cost-effective and familiar alternative for assessing gait kinematics, but more smartphone-based data collection in the real world is needed [93].

Smartphone app based kinematic gait evaluation has been previously validated, but in a controlled laboratory environment and only using the right leg [94]. This thesis identifies this scientific gap.

2.1.2 Assisting the impaired through handheld SLAM-based solutions

2.1.2.1 Museum accessibility enhancement through AR cloud platforms

The improvement of a museum's accessibility necessitates the integration of new technologies in this area and, thus, the utilization of mobile museum applications. The identification of the main features for the design of a museum application can give insightful thoughts for both museum managers and application developers [95]. Curiosity, Usability, Interaction, Motivation and Satisfaction are components that need to be taken into consideration when developing such applications [96].

There is various AR approaches found in museum scenarios aim at increasing accessibility of impaired. Based on the aforementioned factors and the fact that MAR has proven to be beneficial for the deaf visitors of a museum during their visit, a prototype AR conceptual model for the hearing impaired entitled “Hearing Impaired Museum Visitors’ Engagement – MARHIME” has been introduced [97]. To overcome the difficulties during the tour of visitors in a museum, a system based on AR is introduced to predict the optimal routes in a museum [98].

A different approach for guidance and exhibition presentations is the combination of wearable technologies and AR [99]. The case of the Literary Museum [100] illustrates the user engagement that AR offers, even when the visitors have minimum experience with mobile applications. Research integrating AR in a museum for school children with zero experience showcased that AR increases the interest of the visitors and the gained knowledge [101]. The implementation of multimedia AR information systems that can display 3D models of museum artifacts and provide multimedia content to the visitors [102] increases the overall experience of the exhibition. Moreover, combination of such content with Virtual Reality - VR and AR shows increase of engagement in exhibitions [103]. Many statistical techniques and methods are utilized to measure the impact of the implementation of AR and VR in the museum service model, and their results demonstrate they affect the interaction of users with accessibility issues [104].

Since AR is applied widely in museum scenarios, its beneficial capabilities are studied on whether they can support related museum area problems. A field of study in such environments incorporates the use of CV for museum information identification. CV applications conduct state recognition and then object identification to provide the museum visitors an advanced tour [105]. Drawbacks of such solutions, which increase accessibility especially for the impaired, include either the installation of hardware or the requirement of system training via experienced personnel. This identified literature gap and the advanced world capabilities of AR give the motivation for this thesis to solve the museum object recognition problem for the impaired. The thesis proposes intelligent AR approaches via Multi-Tenant AR Cloud platforms for enhanced assisted living to support the deaf.

2.1.2.2 SLAM-based obstacle detection

The scientific community has examined various approaches to provide a solution to the obstacle detection and navigation problem of individuals with visual impairments. Proposals differ from using static hardware installed at certain locations to attaching wearable sensors or combining multiple devices into a distributed system. Following the technological breakthroughs, mobile solutions such as CV and AR have been introduced offering immersive experiences in the users' palm of their hands. How can the utilization of such technologies overcome the drawbacks set from the currently proposed works?

Navigation devices aiming at guiding visually impaired individuals through indoor and outdoor scenarios is a challenging research topic concerning various fields of expertise [106] with solutions differ from using wearable and portable assistive tools [107] to sonar, infrared or optical technologies [108]. Various solutions incorporate the use of GPS or GSM [109] for outdoor localization. Along with the GPS data that are gathered from the mobile phone, tactile feedback from sophisticated haptic hardware is applied to the users' foot [110] for urban obstacle avoidance. The precision of the routing, though, is equal to the GPS error margin. A low-cost solution is the installation of RFID tags in indoor [111] or even outdoor scenarios such as university campuses [112], where RFID is combined with GPS to provide a more precise solution. Another novel approach is the setup of a network of IP Cameras running over LAN. These Cameras, one for each room, utilize custom CV algorithms for person location identification and possible obstacle avoidance [113].

The core limitation of these proposals is the requirement of hardware installation at a specific location, affecting the solution versatility and flexibility. To overcome this, technologies like sonar have been utilized. Sonar navigation systems were initially distributed to common users via portable Pocket PCs generating spatial sounds [114]. More recent approaches have limited down the cost and size of such solutions but maintain the same installation complexity [115]. Moving from the sound to the light spectrum, LiDAR based navigation systems offer a more flexible solution [116]. Advanced LiDAR navigation systems also combine audio instructions [117] or haptic feedback devices for better user information [118], but still require, thus, the utilization of a specific sensor. Recent research developments include the utilization of wearable RGB-D cameras [119] to efficiently identify and detect obstacles for blind and visually impaired people. Related studies examine the use of Smart Glasses which use various methods to identify objects like furniture or stairs and provide feedback through text to speech audio subsystems [120].

Significant research has been conducted in the domain of ML and CV, which are the foundational technologies of achieving object and obstacle detection via Camera devices. Various datasets and models have been created for this pur-pose, an example of whom is a dataset able to recognize ob-stacles in blind sidewalk [121]. More sophisticated solutions include Deep Learning for efficient in indoor and outdoor environment scenarios [122], Convolutional Neural Networks -CNNs for human and scene object detection aiming at user navigation and increased location awareness [123] and fast obstacle detection ML systems via depth image information [124]. ML models like YOLOv3 have been studied [125] for applications running in smartphones, which is a solution that incorporates CV with the proposed principles of mobility and ease of access.

Recent research in the field of Immersive Technologies shows great applicability of SLAM applications in various fields like education [126] and health [127]. The afore-mentioned examples fall within the scope of Metaverse applications, which are delivered to the user through Immersive Displays via either dedicated hardware or mobile devices [128]. They have a positive impact on increasing human perception [129] and understanding human input [130] to achieve optimal Human-Machine interaction. Handheld immersive applications are in the core of such technologies and can act as assistive tools for remote patient monitoring offering solutions for both head mounted displays [131] and mobile commodity devices [132]. The use of AR, a part of Extended Reality technologies [133] shows promising research results in rehabilitation scenarios [134] as a method of applying Gamification techniques. Such serious games, like the ones studied in this thesis, do not only motivate users to increase their physical activity but also provide an efficient way for the healthcare professional to remotely configure the games and, hence, monitor the patients. These SLAM solutions incorporate the rendering of 3D virtual objects combined with the frontal environment of the user's phone. Other similar studies of the thesis demonstrate the utilization of AR into Nature-Based Solutions for enhancing environmental understanding and promoting well-being. SLAM has been used extensively in the field of navigation using mobile device hardware. Research studies show advancements in SLAM-based navigation methodologies [135] with AR applications for both indoors and outdoors being in the core point of interest of the thesis. Moreover, the thesis proposes SLAM navigation assisted by Continuous ML. These results are achieved using the world tracking technologies of SLAM [136] which offer advanced applications: from Cloud and Geographical real-time object manipulation to Lighting and Depth Estimation in the form of real-time Depth-Map extraction [137].

Concerning the implementation of SLAM algorithms, and their applications, there are various open-source approaches [138] with promising results according to recent studies. Results of these studies highlight that OpenVSLAM [139] and ORB-SLAM [140] frameworks are among the most efficient. The SuperPoint-SLAM3 implementation [141] is showing the greatest results among the ORB-SLAM3 framework, by fusing modern deep features with a learned loop-closure module.

Neural radiance fields can be used with SLAM to better reconstruct a scenes as an enhanced 3D-mapping pipeline [142] while another study, DeepFactors [143], demonstrates study towards rich geometry estimation from monocular imagery. These implementations are examples of the state-of-the-art of SLAM and work as fundamental to building efficient AR applications.

The specific field of blind or visually impaired navigation hangs under the broader scope of improving accessibility using immersive technologies [144] with numerous approaches having been studied to date [145]. One of the most interesting assistive AR applications for the visually impaired is a HoloLens system [146] which uses the device to introduce an AR pseudo-color system for assisting individuals with reduced field of view capabilities, like patients with Retinitis Pigmentosa. More recent studies include the use of depth capabilities of mobile AR libraries to capture distances from object and, hence, provide some information about the frontal space of a visually impaired individual [147]. As this study concludes, and it is the pivotal point of the initiation of the current part of the thesis, it is feasible to create system that utilizes mobile AR libraries to provide efficient obstacle detection and navigation.

The thesis solution integrates intelligent technologies into a mobile application capable of running on commodity devices. This application uses newly introduced intelligent algorithms to capture the frontal space, find distances and propose obstacle avoidance indications. Ease of use and accessibility are taken into consideration, allowing this intelligent system to provide voice and haptic feedback for the user, if the phone is not facing the correct direction, acting as a virtual Blind AR White Cane.

2.1.3 Introducing location-aware mobile intelligent systems for navigation and localization

2.1.3.1 AR indoor navigation

Traditional mobile navigation methods retrieve the position of the device either by cellular network [148] or via satellite using GPS [149]. While these methods show positive results giving driving, cycling or walking directions, they lose precision when indoors. The complex indoor environments of healthcare facilities, such as hospitals, nursing homes or doctor office buildings give the visitor or the buildings personnel a devastating experience when they are willing to navigate.

To overcome this limitation, solutions utilizing static hardware attached to a building are introduced. Adam Satan's system uses Bluetooth Beacons which emit radio frequency signals identified by the device before using Dijkstra algorithm to find the shortest path [150]. Following the same concept, but using WiFi signal instead of Bluetooth, indoor navigation was achieved in COEX complex in Seoul [151]. An approach was to identify landmarks and create magnetic maps for multiple corridors of a floor in a building using a phone's built-in magnetometer [152]. All aforementioned examples require modifications and sensor installations in order to produce the desired result. Another proposal, which does not require any kind of sensor installation, is navigation by estimating steps using accelerometer and 5G signals [153].

Keeping aligned with the using-onboard-sensors-only approach, more integrated hardware can be utilized and combined, such as the device's camera for technologies like AR. AR in comparison with Virtual Reality (VR), captures the outside world and interacts with the area in front by attaching and visualizing augmented information [154].

Target indication in facility maintenance operations is an interesting proof-of-concept scenario of AR's [155] localization ability, along with freight car routing [156]. In combination with WiFi/Bluetooth Low Energy signals, Jehn-Ruey Jiang et al. introduced an AR indoor navigation framework [157] which is applicable in both AR for mobile and VR glasses. The scientific base behind these solutions is a combination of feature extraction from a series of images with data retrieved from device sensors, called Simultaneous Localization and Mapping (SLAM). SLAM is identified as a problem [158] with solutions in robotics [159] and more recently in combination with AR [160].

The Googles ARCore Library facilitates indoor space recognition by utilizing SLAM in such a way that enables a device to identify locations previously recorded by other devices. Features from the device's camera feed are recorded, processed and stored to the cloud. Then, they are retrieved by other devices which compare them to what they are recording at runtime [161]. Such feature extraction techniques are used by handheld PCs to identify similar locations in an image database and display location-related information [162] or used in a simulated physical shopping mall environment by utilizing the Vuforia engine [163].

This related work review gives the thesis the opportunity to explore the application of Cloud-based AR solutions for indoor navigation purposes which are valuable especially for impaired persons, where navigation is extremely difficult.

2.1.3.2 ML-enhanced AR localization

Several AR applications have been developed for smartphone platforms, specifically oriented towards user navigation [164]. For example, Milan Metro Augmented Reality is an AR navigation application that guides the user to find metro stations using the camera and location [165]. Another navigation app is Junaio Augmented Reality, which provides various information about local events and promotions, which is displayed directly on the image captured by the mobile camera [166]. In addition, Happy Measure is an AR application that helps the user with room design for interior design [167]. Moreover, at the National Gallery of London, they use AR to offer enriched experiences to their visitors by providing additional information about an object or exhibition [168].

The AR indoor navigation approach yields a positive impact in indoor areas but has one major limitation: it is affected by changes in space. The movement of an object (e.g. a garbage bin) can have a negative effect in the resolving duration or even the whole resolving process of the navigation [169].

AR paradigms can be found also in scenarios where the procedures are enhanced by ML before displaying the appropriate data. An example application in Medicine utilizes the combination of Text Recognition and AR for identifying drugs and displaying the corresponding molecular compounds using 3D AR models. Moreover, AR with ML in Healthcare research aims towards improving the understanding of a surgical scene [170] while discrete manufacturing is another case where such technologies may be used in combination [171]. In Education, ML Object Detection is utilized to facilitate teaching alphabet writing [172] via a mobile AR application.

The problem of AR not easily adapting to space changes was identified at the process of the thesis and revealed a scientific gap. The utilization of ML gave the motivation to the thesis for research in the field of combining AR with ML for more efficient indoor positioning. This is an intelligent system which facilitates better navigation and better assisted living for indoor navigation systems, enhancing accessibility for the impaired.

2.1.3.3 AR gamified crowd management

Crowd management in museums and exhibitions has been approached by various methods which re-route the visitor, try to provide additional information and increase accessibility. The use of IoT for visitor tracking [173] and Neural Networks for path planning and reconstructing visitor trajectories [174] is an example scenario of such implementation. Other studies include the installation of a robotic system [175] to deliver content and perform crowd counting.

Gamification is a technique that is used in this research to engage the users and motivate them to avoid a crowded section, but it is not the first time that it is used in exhibitions. Current focus is on creating game add-ons to existing exhibitions but there is a lack of theory and tools [176]. A methodical review of the literature between 2015 and 2020 shows that novel gamification approaches are used for promoting cultural heritage [177]. In this thesis, gamification elements are going to be introduced using AR technology for exhibition areas accessibility.

AR for mobile devices is in the center of the scientific interest with applications in various fields. For instance, in the tourism industry, AR [178] can display city landmarks in 3D while it is also studied in exhibition areas for exhibit recognition via Multi-Tenant AR Cloud Platforms in this thesis. A prototype mobile AR exergame system is studied in the thesis on whether it increases physical activity with the utilization of IoT and a remote monitoring platform. AR with gamification elements can also be found in this thesis in the form of augmented badges and leaderboards for NBS visit motivation. Moreover, AR is used in the thesis for indoor navigation and positioning using Cloud Anchors and implementing SLAM [179].

AR in a museum scenario is studied in surveys as a communication medium [180] and used also by robots to localize themselves in the museum before providing a tour [181]. An AR based museum guidance system is also introduced using handheld Ultra-Mobile PC [182] while museum navigation, interactive content and mixed reality games are also introduced using handheld devices [183]. In the museum example case of Casa Batllo in Barcelona AR is used for an enriched experience while visiting the site [184] while a different approach uses immersive audio augmentation to make the audio guide more interactive [185]. Crowd management using the approach of AR is studied to re-route users to other museum paths [186].

The thesis combines Gamification and AR to overcome the issues of crowd management by introducing a set of algorithms for identifying the crowd and a series of AR serious games to engage keeping the users waiting, while requiring no additional hardware or any kind of installation, eliminating thus any possible additional cost. This solution defines an intelligent system that facilitates accessibility and increases users' motivation for visiting and education.

2.1.4 Facilitating medical education through AR and CV

Advancements in CV and particularly in Augmented Reality (AR) lead to the creation of innovative solutions with an emphasis on human-machine interaction principles. AR technologies can support education in various domains and especially in health and are already compatible and accepted for modern healthcare services provision [187]. A key benefit of incorporating AR solutions in health is the hands-free experience [188] which also highlights the sense of presence AR provides [189]. Hence, the intention for using such technologies has a positive perception from the healthcare community [190].

AR supports education in different domains of everyday life [191] [192]. Specifically, AR solutions in healthcare use either mobile or wearable devices and glasses [193] to support medical [194] [195] and anatomic [196] education and healthcare professionals training. AR technologies can also be applied for better drug management and to support patients' adherence for drug intake [197] [198]. Moreover, AR is used for educational proposes in science [199] and especially in chemistry [200]. The advanced visualization capabilities AR provides are found to have positive impact when displaying educational material of proteins and ligands [201].

An interesting approach includes the incorporation of AR with classic image recognition technologies to recognize the area via CV and display digital content using AR. Related studies include the display of information from drug data [202]. Additionally, Optical Character Recognition (OCR) methods are used to identify text of medicine box before displaying 3D AR model of the affected body part [203].

The literature review indicates possibilities when combining AR with CV identification algorithms and highlights the literature gap of using CV do identify a drug and display molecular compounds via AR.

2.2 Fundamentals

The methodologies that are presented require fundamental theoretical knowledge, domain-specific terminology, understanding of the workflow of algorithms, inputs and outputs, to better understand the identification of the problems that they try to solve.

2.2.1 Theoretical foundation

This subsection describes the theoretical background of the terms of Assistive Environments, Patient Monitoring, Gamification, Exergames, Nature-Based Solutions and gait analysis fundamentals.

2.2.1.1 Patient Monitoring

Patient Monitoring refers to the continuous or periodic observation and collection of health-related data to assess a patient's physical and physiological condition. It involves the use of sensors, wearable devices and digital platforms to track metrics such as heart rate, blood pressure, oxygen levels, and activity levels.

2.2.1.1.1 Applications

Applications of Patient Monitoring include chronic disease management, post-operative care, elderly care, and fitness tracking. Advanced systems integrate IoT devices and cloud-based platforms to enable Remote Patient Monitoring, where healthcare providers can access patient data in real time.

2.2.1.1.2 Relevance to the Thesis

Patient Monitoring plays a key role in this thesis by providing the foundational data required for intelligent healthcare systems. The proposed systems incorporate wearable sensors and IoT devices to track patient activity levels, detect gait asymmetry, and monitor overall health. These monitoring capabilities are seamlessly integrated with gamification and AR technologies to encourage physical activity and improve patient outcomes, particularly in Ambient Assistive Living environments.

2.2.1.2 Assistive Environments

Assistive Environments refer to physical or virtual spaces enhanced with technologies designed to support individuals in performing daily activities, improving their quality of life, and promoting independence. These environments are particularly beneficial for elderly individuals, people with disabilities, and patients requiring continuous care. Assistive technologies integrated into these environments include sensors, IoT devices, AI and AR, which enable adaptive and personalized support.

2.2.1.2.1 Relevance to the thesis

This thesis focuses on utilizing Assistive Environments to improve patient health outcomes through intelligent systems. By integrating AR, IoT, and AI technologies, the proposed systems create an adaptive and interactive environment for patient monitoring and health management. The thesis activities also enhance user engagement by incorporating gamification techniques and promoting physical activity in assistive spaces.

2.2.1.3 Gamification

Gamification is a technique which proposes the use of game elements in non-game contexts for achieving a serious goal. It is proven that it increases user **engagement and motivation while keeping the user in the center spot.**

2.2.1.3.1 Prototype Methods

Commonly used Gamification methods are:

- Leaderboards: an ordered list including all players of a game, ordered by their in-game performance. The goal is to put the player in comparison with others, to increase the challenging and competitive mentality, resulting, thus, in user engagement.
- Badges: a set of achievements when reaching a certain block of a leaderboard or an in-game milestone. This achievement motivates the player to continue playing and unlocking the next achievement, engaging the player into the game.

2.2.1.3.2 Relevance to the thesis

In this thesis Gamification is used in various approaches: from plain AR prototypes which utilize gamified elements to increase users' steps, to complete AR games which simultaneously monitor the user's health combined with IoT. Additionally, it is used to engage users visit "pocket-parks" using the techniques of Badges and Leaderboards. Finally, it is found to have positive impact in intelligent crowd managing systems for exhibition areas.

2.2.1.4 Nature Based Solutions

Nature-Based Solutions (NBS) leverage natural ecosystems to address social challenges and provide environmental, social and economic benefits.

2.2.1.4.1 Conceptual Framework

The International Union for Conservation of Nature defines NBS as “actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits”.

2.2.1.4.2 Applications and challenges

A common application of NBS is found in densely populated urban areas commonly called “concrete jungles”. These solutions incorporate the conversion of an empty block into a small park, called “pocket park”, enhancing green infrastructure, improving the quality of air and motivating citizens to increase their physical and mental activity.

2.2.1.4.3 Relevance to the thesis

This thesis proposes a system that utilizes an NBS for increasing visitors’ physical activity in combination with intelligent technologies. Such technologies include AR and IoT.

2.2.1.5 Exergames

Exergames are a set of games that use Gamification elements to motivate the player to do more exercises, having a positive health impact.

2.2.1.5.1 Common Applications

Various applications can be defined as exergames like video game consoles which require the user to perform certain actions or, more recently, AR games that motivate the user to walk to play the game.

2.2.1.5.2 Relevance to the thesis

Exergames are used in this thesis to achieve physical activity increase of the patients, crowd management in exhibitions and user education. They are doing so by introducing a set of AR games which require the user to walk and catch the answers, increasing their step count while having a pleasant time.

2.2.1.6 Gait fundamentals

Since part of the current dissertation includes research on gait asymmetry detection in RPM scenarios, some gait fundamentals are essential to be presented.

2.2.1.6.1 Gait cycle

The term gait cycle refers to the description of a movement pattern that occurs while walking. It is standardized as follows: the beginning is the initial contact of the foot (0%), and the end is the next contact of the same foot (100%). It is divided into two phases, the Stance Phase and the Swing Phase, each with specific characteristics [204]:

The Stance Phase accounts for 60% of the total gait cycle, during which some part of the foot is in contact with the ground. It begins with the Heel Strike, which is the initial contact and corresponds to the moment when the heel of the reference leg touches the ground while the other leg is terminating the stance phase (double support time). It is followed by the Loading Response, the period when the reference foot is fully in contact with the ground and the other leg is initiating swing phase (pre-swing). The Mid-Stance is the state where the body weight is completely on the reference leg while the other leg is between initial and mid-swing phases. The Terminal Stance starts as soon as the heel of the reference leg starts moving away from the ground, but the toes are still in contact with the ground and the other leg follows Terminal Swing. Finally, the Toe Off state describes the acceleration for propulsion and the reference foot starts moving further keeping toe in contact with the ground while the other leg is in loading response [205].

The Swing Phase occupies 40% of the total gait cycle, during which the foot is not in contact with the ground and the body weight is borne by the other leg. The first sup-phase of Swing is the Initial Swing and represents acceleration. It includes the forward motion of the limb which starts with knee flexion. The foot loses contact with the ground and starts dorsiflexion. The Mid-Swing occurs when the reference leg is in the air and with gait triple flexion (hip, knee, ankle) and is followed by the Terminal Swing, the deceleration in which the reference foot is positioned for initial contact to start the next gait cycle [206].

2.2.1.6.2 Relevance to the thesis

The understanding of the basic gait principles gives the reader a broader perspective of the gait asymmetry detection by explaining the phases of the gait cycle. This knowledge is vital to understand the proposed solution of the thesis which introduces a method for monitoring gait asymmetry (of both legs) using only a single sensor.

2.2.2 Technical foundation

This section outlines the technical concepts and technologies that form the backbone of the proposed systems in this thesis. The discussed technologies include hardware and software components essential for achieving the desired objectives in Ambient Assistive Living environments. These foundational technologies—ranging from sensor-based systems like Inertial Measurement Units to advanced computational methods like Simultaneous Localization and Mapping—are critical to understanding the thesis's architecture and implementation strategies. The integration of Augmented Reality and Internet of Things further enriches the solutions proposed, enabling novel approaches to healthcare monitoring, gamified systems, and user engagement.

2.2.2.1 Commodity Mobile Devices

Commodity mobile devices, such as smartphones and tablets, are ubiquitous and widely available electronic devices equipped with advanced sensors, processing power, and communication capabilities. These devices often include cameras, accelerometers, gyroscopes, magnetometers, and GPS modules, making them ideal platforms for implementing various intelligent systems.

2.2.2.1.1 Relevance to the thesis

This thesis exclusively utilizes commodity mobile devices as a key component of the proposed systems. These devices are used for running AR applications, collecting and processing data from wearables and IoT sensors, and providing real-time feedback to users.

2.2.2.2 Inertial Measurement Unit

The Inertial Measurement Unit (IMU) is an integration of sensors which measure force, angular velocity, orientation and magnetic signals in the three-dimensional space. The IMU is foundational in modern navigation, tracking and motion analysis systems.

2.2.2.2.1 Key Components

A typical IMU integrates Accelerometers, Gyroscopes and Magnetometers:

- Accelerometers: they measure linear acceleration along X, Y and Z axes
- Gyroscopes: they measure angular velocity along X, Y and Z axes in the form of rotation rates
- Magnetometers: they measure local magnetic field vectors for aiding heading estimation and drift correction

2.2.2.2.2 Applications and Limitations

IMUs are applicable in environments where GPS signal is poor or where there is no other form of motion tracking like underwater, indoors or in space. Their widely adoption in robotics and AR provides advanced motion tracking capabilities but they suffer from cumulative integration errors (drift) which deviate the estimated position. Their best use is when they are integrated with other modalities like depth or visual data.

2.2.2.2.3 Characteristics

The following table gives insights to the IMU sensor characteristics, highlighting size, accuracy, power, sampling rate, latency and integration with other modalities.

Characteristic	Description	Installation Example
Size	IMUs vary from chip-scale sensors to large, ruggedized aerospace units.	MEMS-based IMUs in smartphones and fitness trackers are integrated into small PCBs.
Accuracy	High-grade IMUs offer low drift, while consumer-grade units drift more quickly.	Aircraft autopilot systems use navigation-grade IMUs; drones use consumer-grade IMUs.
Power	Ranges from ultra-low power (wearables) to higher power (industrial systems).	Smartwatches use low-power IMUs; submarines rely on higher-power precision IMUs.
Integration	Often fused with GPS, cameras, or LiDAR to improve accuracy.	Autonomous vehicles combine IMUs with LiDAR and cameras for reliable navigation.
Sampling Rate & Latency	High-performance IMUs provide fast updates with minimal delay.	VR headsets use high-frequency IMUs for smooth and responsive tracking.

2.2.2.2.4 Relevance to the thesis

IMUs are used across various prototypes that are developed in the thesis research activities. They are a fundamental modality for all AR systems of the thesis, and they are also used for achieving RPM through hand trembling monitoring and gait asymmetry detection. The IMUs that are used in the thesis are strictly integrated in commodity devices and no external hardware is used. Such usage would violate the initial scope of the thesis.

2.2.2.3 Simultaneous Localization and Mapping

SLAM stands for Simultaneous Localization and Mapping. SLAM algorithms achieve surrounding area recognition by utilizing camera feed along with data from device IMU sensors. Feature points from certain and dense segments of each camera frame are extracted while the area is steadily scanned. Raw data from IMU sensors (accelerometer, gyroscope) in combination with the feature points create a 3D representation of the foreground scene allowing, thus, the placement of objects relevant to these points. This technique requires some computational power resulting, thus, in a limitation of simultaneous area searches.

2.2.2.3.1 Characteristics

The following table demonstrates key characteristics of SLAM, including sensor fusion, mapping capabilities, localization accuracy, computational complexity, real-time operation and scalability.

Characteristic	Description	Installation / Application Example
Sensor Fusion	SLAM integrates camera data with IMU measurements to reduce drift and improve accuracy.	Mobile AR platforms fuse visual-inertial odometry for stable tracking.
Mapping Capability	Builds a consistent map of the environment while simultaneously estimating the device position.	Autonomous vacuum robots build real-time maps of indoor layouts for navigation.
Localization Accuracy	Provides centimeter-level precision in controlled environments but may degrade in feature-poor or dynamic scenes.	Drone-based SLAM ensures precise localization in GPS-denied environments like caves or indoor warehouses.
Computational Complexity	Requires significant processing for feature extraction, point cloud alignment, and optimization.	AR headsets rely on GPU/CPU acceleration to handle SLAM in real time.
Real-Time Operation	SLAM must update continuously with low latency to be useful in interactive or autonomous systems.	AR navigation apps update user position in real-time as they move through complex indoor spaces.
Scalability and Drift	Works well in small to medium spaces; drift accumulates in larger	Self-driving cars use loop-closure techniques and LiDAR-

	areas without loop closure or global correction.	visual SLAM to maintain accuracy over long distances.

2.2.2.3.2 Relevance to the thesis

SLAM is the fundamental technology of AR systems which are widely developed across various prototypes of the thesis. Hence, the understanding of the basic SLAM principles provides the reader with knowledge of the way the developed systems work. It is an intelligent technique with various implementations and by explaining its workflow, research questions which facilitate SLAM effectiveness are justified.

2.2.2.4 Augmented Reality

An immersive human-machine-interaction experience is achieved without the need of additional hardware. By utilizing onboard camera and IMU sensors, the phone's video feed can be supplemented with additional augmented information such as labels, images, markers and other kinds of multimedia. A marker's position remains attached at the predefined location regardless of any device movement or environment change.

2.2.2.4.1 Anchors and Planes

Digital items attached in the foreground scene are referred as AR Anchors due to their ability of remaining static at a surface. Such surfaces, that allow Anchor placements and persistence, are referred as AR Planes. Any device movement (even change of rooms) will not affect the AR experience as it relies itself on a SLAM technique. Attaching an Anchor to a Plane requires software that implements SLAM.

2.2.2.4.2 Cloud Anchors

Local area identification and localization is achieved by extracting features of an image feed along with data from device IMU sensors. At first, the area around the device needs to be slowly and steadily scanned. While scanning, the SLAM algorithm parses the camera frame feed and extracts feature points from each frame. These algorithms are optimized to focus on certain and dense segments of each image to achieve better data processing. Extracted features are combined with data from the IMU sensors to determine the exact distance, rotation and orientation of the recorded frames. Segments of the feed that have a confident number of features offer the ability to attach Anchors to the scene, considering that the nearby features of an Anchor can be easily recognized once the device reaches that spot. Cloud Anchors functionality gets use of a SLAM output as a base to store Anchor locations for remote use. Goal of Cloud Anchors is the ability to preview Anchors that were placed by another device in the past. Hence, feature points in the range of an Anchor are captured and stored in a cloud database. By providing a camera feed from the same area and comparing the current extracted features with the database, the exact position of an Anchor can be precisely estimated. Limitation of the aforementioned capability is the bounded amount of Cloud Anchors that can be searched at the same time.

2.2.2.4.3 Relevance to the thesis

AR is the primary technology used in most of the thesis solutions. The reason for this is that it achieves high levels of Human-Computer Interaction, providing the users a pleasant and immersive experience. This experience and the high “wow” factor facilitate user engagement and, thus, exploit AR applications for achieving more serious goals. The specific AR terminology is mandatory for understanding architecture and implementation practices while the extensively explained Cloud Anchor workflow highlights the benefits of this intelligent procedure.

2.2.2.5 Internet of Things

Internet of Things (IoT) is a computing paradigm of equipping everyday physical objects with sensors, processing units and communication capabilities enabling for seamless data interchange over digital networks. The IoT concept extends the scope of internet beyond human operated interfaces to automated systems. Key characteristics are the autonomous data manipulation, the decision making and the intelligence in computations.

2.2.2.5.1 Characteristics

The following table gives insights to the IoT sensor characteristics.

Characteristic	**Description**	**Installation Example**
Intelligence	IoT devices are not only measuring data through their onboard sensors, but have also computational power and can perform dedicated processing tasks.	IoT cameras, Smartwatches
Size	Their size can vary from a tiny device to a pocket-size and a larger device that requires continuous power.	Health monitoring ring, Smartwatch, Weather sensor
Connection	Key characteristic of IoT is the device connection with the respective cloud service to upload or retrieve data.	Autonomous IMU sensors, IP cameras.

2.2.2.5.2 Applications and challenges

IoT are found across various domains like smart cities, industrial automation, healthcare monitoring and transport. For instance, widely used IoT devices are wearable sensors like smartwatches or smart bands. Moreover, IoT sensors facilitate understanding of environmental conditions and are incorporated to complete information systems which utilize this data for other purposes.

Challenges of IoT are the constraints of scalability, the security and privacy risks arisen from distribution of processing, the interoperability issues which are based on the manufactured of the hardware and the energy limitations, especially in small devices which small batteries.

2.2.2.5.3 Relevance to the thesis

IoT devices are used in this thesis in three scenarios:

1. In combination with AR: to facilitate RPM while playing AR exergames. They are used in form of wearable watches – smart watches and they record vital signs of the user. These signs are transmitted afterwards to the mobile phone before being uploaded to the cloud for the healthcare professional to live monitor the patient.
2. In NBS to record both users' physical activity and to record temperature and humidity. A set of smart bands are provided to the users to monitor their physical activity. This data is uploaded to the cloud and inserted into a Leaderboards & Badges gamified system. Moreover, various environmental measurements are captured and displayed to the visitor as AR Anchors, enhancing user engagement and willing to explore the NBS.
3. In gait asymmetry detection, to record motion data from the user smart watch.

3 Proposed Methodology

This section contains methodological information about the proposed solutions described in this thesis. It consists of subsections for Requirements, Design, Architecture and Implementation. Each subsection is divided into the studied fields, which are categorized as previously for consistency:

1. **Engaging users for increasing their physical and mental activity and RPM using AR, IoT and IMU technologies**
2. **Assisting the impaired through handheld SLAM-based solutions**
3. **Introducing location-aware mobile intelligent systems for navigation and localization**
4. **Facilitating medical education through AR and CV**

3.1 Overview and design of the proposed solutions

This section provides an integrated overview and detailed design of the proposed solutions developed within the framework of this thesis. Each solution aligns with the research pillars and aims to address specific challenges in advancing electronic healthcare and Ambient Assistive Living environments through computational intelligence. The proposed solutions are built upon state-of-the-art technologies such as AR, CV, IoT, and SLAM. The design process focuses on leveraging these technologies to create intelligent, scalable, and hardware-independent systems that enhance user engagement, accessibility, and healthcare delivery. For each research focus area, we identify key requirements, outline the system architecture, and present the design methodologies adopted to achieve the desired outcomes. By combining innovative algorithms, modular architectures, and user-centric approaches, the solutions aim to bridge existing scientific gaps and provide actionable contributions to the field of intelligent healthcare systems.

3.1.1 Engaging users for increasing their physical and mental activity and RPM using AR, IoT and IMU technologies

This subsection focuses on the integration of AR, IoT, and sensor technologies to design intelligent systems that enhance user engagement and facilitate Remote Patient Monitoring (RPM). By leveraging commodity mobile devices, wearable IoT sensors, and advanced AR techniques, the proposed solutions aim to motivate users, monitor their health metrics, and provide real-time feedback, all within cost-effective and accessible frameworks.

3.1.1.1 Gamified AR and IoT platforms for remotely assessing physical activity

In this thesis, we have developed an Augmented Reality (AR) platform [234][231] that combines gamification and IoT technologies to promote physical activity and enable real-time health monitoring. The system integrates AR exergames with IoT wearables, creating engaging, interactive experiences while tracking users' vital health metrics. To engage users and increase their physical and mental activity, research in this domain requires the following:

Objectives	Description
User Engagement	Development of gamified AR applications that encourage users to participate actively in physical exercises and rehabilitation routines
IoT Integration	Seamless integration of IoT devices (e.g., wearables, commodity devices with IMU sensors) to collect rich multimodal data, including activity levels, gait patterns, and contextual information.
Accessibility	Platforms must be cost-effective, portable, and easy to use for diverse patient populations.
Data Analytics	Real-time data processing and feedback mechanisms to motivate users to adhere to prescribed activities

This platform answers the following: **Question 1, Question 2 and Question 3.**

The developed prototype is a form of an interactive serious game quest which, by using AR, displays objects in a local home environment and challenges the users to interact with them. At the same time, users' biometric data are logged for local and remote monitoring. These data are recorded with both built-in mobile device sensors and with the use of IoT wearable devices, such as smartwatches. A web interface is also introduced, which has the role of supervising the game sessions and configures the gameplay parameters and scenarios. Using this interface, a corresponding healthcare professional can monitor the progress of the users, reconfigure the game parameters, and analyze the game and health monitoring results. An overview of the approach is presented in Figure 1.

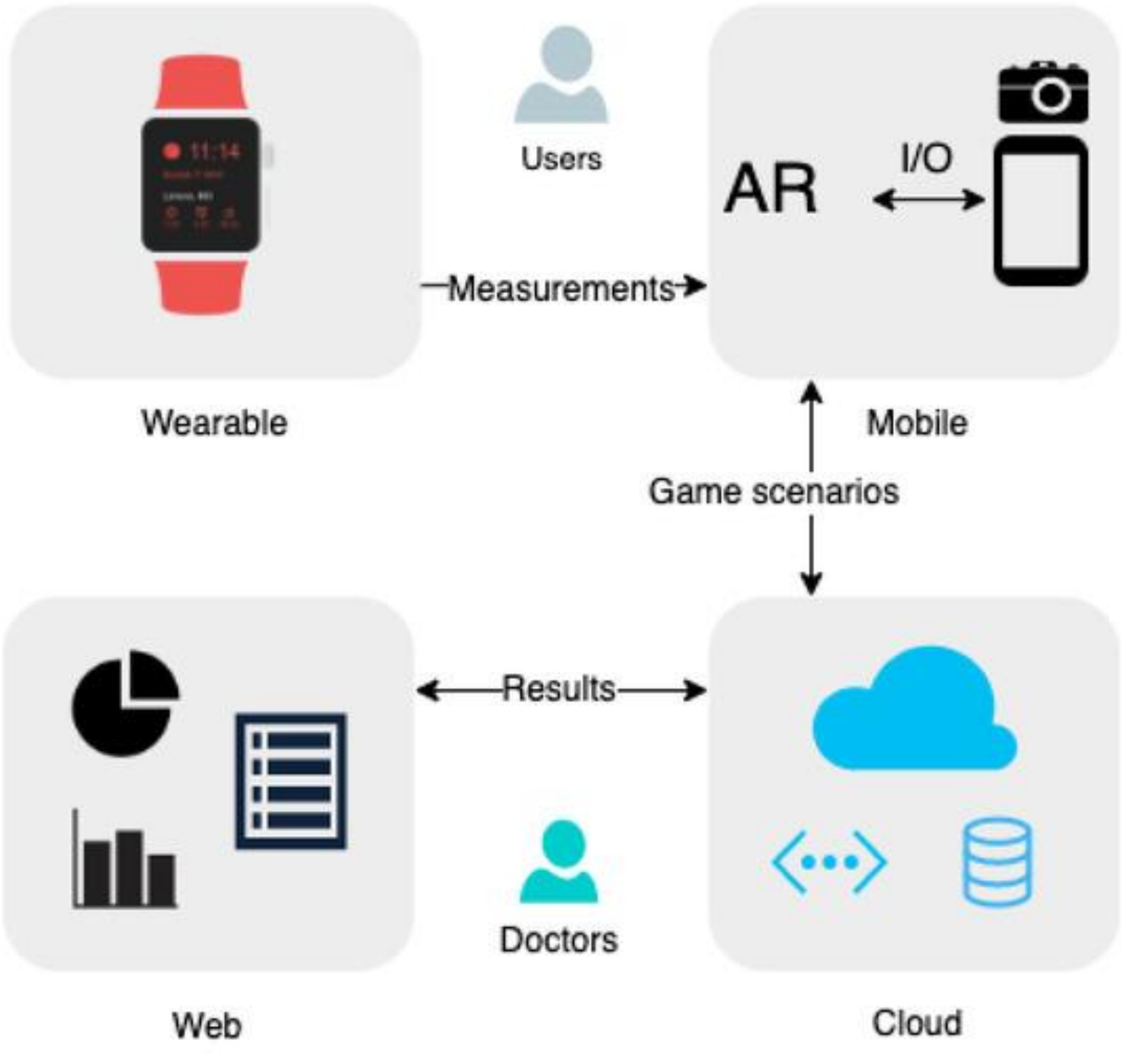

Figure 1: The overview of the system. It shows the Wearable and Mobile commodity devices which are utilized for health data recording and AR exergame execution. Data are transmitted to the Cloud platform from which the doctor's Web interface pulls and displays data in real time.

3.1.1.2 Cloud-Enabled Gamification to Enhance Participation in Nature-Based Solutions

In this thesis, we have designed a gamified AR platform that leverages IoT data and cloud infrastructure to motivate users to engage with Nature-Based Solutions (NBS) [235]. To enhance user participation in NBS, increasing their activity, research in this domain requires the following:

Objectives	Description
Cloud Infrastructure	Development of cloud-enabled systems for scalable data storage and processing to support gamified experiences in outdoor settings.
Nature-Based Activities	Gamification designs must facilitate participation in wellness-promoting activities like walking, hiking, or running in natural environments.
User Personalization	Algorithms for adapting gamified content based on user preferences, physical capabilities, and health goals.
Data Analytics	Real-time data processing and feedback mechanisms to motivate users to adhere to prescribed activities.

Research questions answered: **Question 1, Question 2, Question 3 and Question 5.**

The proposed platform aims at increasing the user's motivation for visiting a park, in which an urban planning intervention takes place, by utilizing AR, wearable devices and IoT create a unique environment with real-time information and gamification quests. The concept of this application paradigm is illustrated in Figure 2.

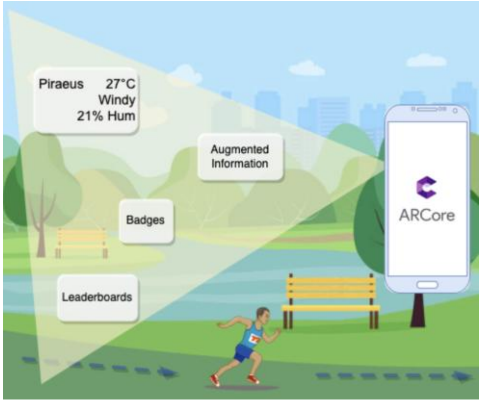

Figure 2: Conceptual illustration of the proposed gamified solution. It incorporates AR Cloud Anchors for NBS visit motivation and physical activity increase.

The system is fed with a variety of data visualized in a way that will increase the user's willingness to visit the park. All data are generated in real-time and can be changed dynamically while a user is in-session. By blending virtual and real world, AR facilitates the user adoption and increases the scopes of the local interventions. Data are divided in two general categories, Location-based information and user-specific information.

3.1.1.2.1 Location-based Information

Location based information are data records which are considered to be useful for the user of nearby attractions or activities. They also include navigation data providing onscreen directions leading the users to either a desired spot or reveal a certain route. Furthermore, weather and environment data retrieved from local IoT sensors are displayed in their precise location and are updated in real-time.

3.1.1.2.2 User-specific Information

User-specific information are personal, health-related data elements that are different for each user and include health and fitness measurements as well as badges and leaderboards in the scope of gamification features of the system.

Gamification elements are the means to motivate users to use their wearables and become more active in their daily lives. In addition, the system encourages users to become more social by rewarding them with badges when they are moving in public spaces such as parks. All data used by the gamification elements are generated by wearables, smartphone devices, or fitness trackers that are compatible with the platform and support direct (via Bluetooth) or indirect (via Cloud) data exchange. The system can recognize the physical activities when the user uses his/her wearable device. Several metrics are used in the system in order to design the gamification elements: 1. total daily steps, 2. distance, 3. duration of physical activities and sleep, event related to user activities or visits to the public space area.

Leaderboards are visual representations of users' ranking in certain aspects. Leaderboards can have the form of ranking/scoring tables and every user can view his performance and compare it with performance that other users have. The current study exploits anonymized graphs as Leaderboards that allow the users to view their ranking in the system. Cumulative charts and distribution charts are used for this purpose. In this way the system shows the user's position in the charts, hiding details that are related with other users' personal data.

Badges represent the users' achievements based on the goals completeness. The user interface is designed in order to address the main objective that is to provide feedback on the users' progress and educate them on how to accomplish their goals. Some cases that are used for badge concepts are the total accumulated steps, completing a minimum number of steps each day, visiting a defined public area every day, and others. During the period that the users try to complete their goals, every badge is represented as a widget in the user interface that shows the progress and the effort needed to complete the final goal. Additionally, every time the goal is completed, the user is rewarded with the relevant badge by visiting the park defined by the application.

3.1.1.2.3 Data Visualization

A problem needed solving was the way in which the virtual objects will appear in their correct position within the park for all system users. The proposed solution was the utilization of SLAM for mobile devices. Taking as example the weather AR label, the label will first be placed using a mobile device. Once the label is attached, the area around it will be converted to features and then uploaded to the Cloud. These features can be resembled as a panoramic image of the area around the label. When another user with a different device reaches the same area and opens his mobile device's camera, a computer vision algorithm will try and match the previously recorded features with the front area. If the feature map identifies a known area, the virtual object is automatically attached to the scene and, thus, placed at the precise location it was set. While location selection will be performed once, resolving and attaching procedure can be done from various devices.

3.1.1.3 Remote gait asymmetry detection

In this thesis, we have developed a mobile-based solution that utilizes built-in IMU sensors to detect gait asymmetry, offering a cost-effective and accessible approach for remote monitoring of mobility impairments [239]. To remotely monitor gait asymmetries at home, utilizing only commodity hardware, the following objectives are determined:

Objectives	Description
Sensor Fusion	Development of algorithms to combine data from commodity device IMU sensors (e.g., accelerometers, gyroscopes) to detect gait asymmetry.
Accuracy and Reliability	Benchmarking against dedicated medical-grade sensors to ensure accurate and reliable detection

Remote Monitoring	Implementation of lightweight software solutions enabling real-time gait analysis without requiring sophisticated hardware

Research questions answered: **Question 1, Question 2, Question 3 and Question 5.**

The primary objective of this part of the thesis is to identify gait events and provide a valid gait analysis result, without the need for any additional hardware apart from the patient's mobile phone. Hence, a measurement protocol has been developed which has the form of instructions on how to set up and use a prototype application. The application records gyroscope and accelerometer data in real time from the phone's sensors. Once the required data is recorded, a set of pattern recognition algorithms is executed to identify and evaluate the data.

To achieve this goal, a cloud platform is designed and implemented alongside a mobile application. An overview of the proposed system is displayed in Figure 3.

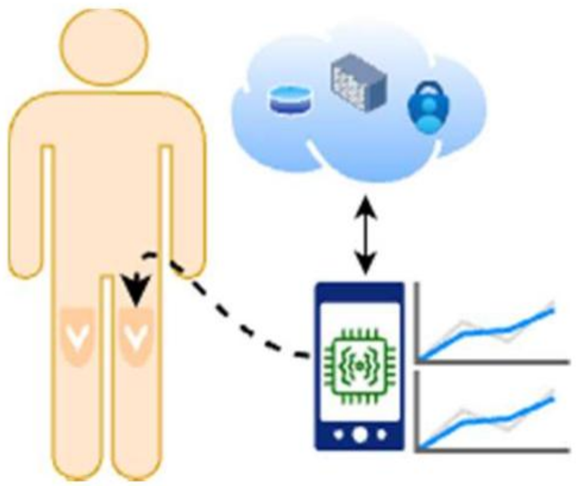

Figure 3: Overview of the proposed gait asymmetry detection system. Gait data are retrieved from the IMU sensors of a commodity mobile phone. Results are displayed in the phone application and uploaded to a cloud server for remote monitoring.

3.1.2 Assisting the impaired through handheld SLAM-based solutions

This subsection explores the development of intelligent assistive environments that leverage AR and SLAM technologies to enhance accessibility and user interaction.

3.1.2.1 Museum accessibility enhancement through AR cloud platforms

This thesis presents an AR-based solution to improve accessibility in museums by enabling efficient exhibit recognition and interaction without the need for static installations [237]. Primary research objectives:

Objectives	Description
Object and Location Identification	Development of AR systems with CV capabilities to identify objects and locations in exhibition settings, specifically for visually impaired users
Multi-Tenant Platforms	Solutions applicable to multiple environments (e.g., museums, hospitals, public spaces) for broad applicability.
Assistive Feedback	Incorporation of audio or haptic feedback mechanisms to aid navigation and accessibility.

Research questions answered: **Question 1, Question 2, Question 5 and Question 6.**

The proposed system provides advanced user interaction functionalities for creating rich experiences to the users and addressing accessibility issues in exhibition areas and related environments. The system consists of two main elements:

A. Multitenant Cloud Platform for AR-based POI Resolution: a generic AR-based platform which is capable of real-time identification of relevant POIs - Points of Interest in a context-aware manner.

B. User Application: a prototype mobile app which is integrated with the cloud platform to provide the aforementioned functionalities to users in the world scenario of a museum.

The mobile app is classified in the category of museum applications that have as main target to provide additional help and ease the accessibility issues, especially of hearing-impaired people. Through the integration with the Multitenant Cloud Platform for AR-based POI Resolution and the customization of the operational parameters for the usage scenario, a set of features for advanced interactivity become available to the User Application.

Figure 4 presents an overview of the system's design and its core functionalities. The users, as visitors of the exhibition/museum, which are equipped with the app installed in their mobile phones, can open the camera to identify exhibits and other points of interest, without the need to use other tools or mechanisms (such as QR codes), and in turn view related rich multimedia for the identified object.

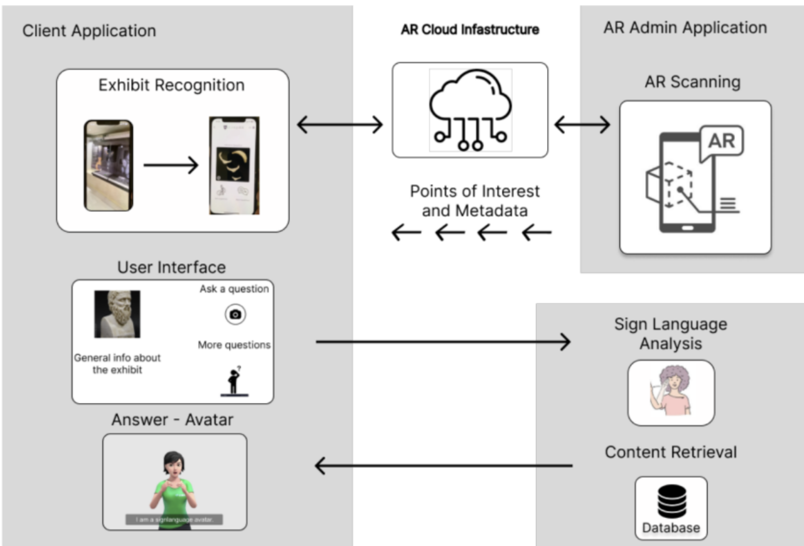

Figure 4: The overview of the system. The Client Application utilizes parts of the Cloud AR system to provide the user with AR object recognition capabilities, trained by the AR Admin Application. The Cloud Platform manages the flow of the data.

3.1.2.2 SLAM-based obstacle detection

This thesis introduces a SLAM-powered mobile application that detects obstacles and cliffs in real time, enhancing accessibility for visually impaired individuals [233]. Primary objectives:

Objectives	**Description**
Depth Estimation	Advanced processing of depth data from SLAM systems to detect and classify obstacles in real time.
Assistive Features	Integration of eHI to provide actionable insights for navigation, especially for individuals with disabilities.
Safety and Reliability	Solutions must prioritize user safety by ensuring high accuracy in obstacle detection and avoidance.

Research questions answered: **Question 1, Question 2, Question 5 and Question 6.**

The extensive study of AR and SLAM in the thesis concluded that SLAM-based solutions can be applied to scenarios which can help the impaired. A primary goal of this part of the thesis is the development of a novel application that can be used by the visually impaired to: monitor the frontal space, identify obstacles and provide indication for avoiding them utilizing depth capabilities of AR. Characteristics of the proposed system encompass the identification of objects (columns, buckets, trees) and the determination of uphill or downhill cliff. To accomplish this, raw depth data are extracted from the AR as a 2D image with each pixel encoding information about the corresponding depth. Subsequently, these data are inserted into a newly designed Object Detection Algorithm. A mobile application is developed which facilitates efficient and lightweight object detection without the need of specific data training or sophisticated hardware.

3.1.3 Introducing location-aware mobile intelligent systems for navigation and localization

This subsection focuses on leveraging AR and SLAM technologies to create intelligent systems for indoor navigation, dynamic localization, and crowd management in healthcare and related environments.

3.1.3.1 AR indoor navigation

This thesis proposes an AR-based indoor navigation system using SLAM to provide precise, infrastructure-free guidance in complex environments [238].

Objectives:

Objectives	**Description**
SLAM Technology	Utilization of SLAM algorithms for mapping and navigation in indoor healthcare environments without prior maps
Commodity Hardware	Solutions must be deployable on commodity devices (e.g., smartphones, tablets) to ensure accessibility.
User-Friendliness	Development of intuitive interfaces to facilitate navigation for patients, caregivers, and healthcare staff.

Research questions answered: **Question 1, Question 2 and Question 5.**

The proposed AR indoor navigation system ingrates specially developed algorithms, manages their parameters and offers a client application which is accessible by the end-users. The users, which have the client application installed into their mobile devices, are able to reach their selected destination guided by on-screen AR instructions, without the need of additional hardware interventions. AR components are configured to identify the specific area and initialize the routing algorithm. Configuration of the system's functionality is performed through limited access applications which are responsible for content creation and management. Figure 5 shows an overview of the AR navigation system comparing the frontal space with its augmented illustration to display the AR navigation arrows.

Figure 5: The overview of the AR navigation system applied to a real-world scenario. When the area is scanned, navigation arrows are showing the path to the destination.

3.1.3.2 ML-enhanced AR localization

This thesis introduces a Continuous Machine Learning (CML) approach to enhance AR localization, enabling dynamic adaptation to environmental changes [232]. Objectives:

Objectives	Description
Machine Learning Integration	Application of machine learning models to improve localization accuracy in AR-based navigation systems.
Dynamic Adaptation	Systems must adapt to changing indoor conditions (e.g., moving objects, altered layouts) in real time.
Resource Efficiency	Efficient use of computational resources to ensure smooth performance on edge devices.

Research questions answered: **Question 1, Question 2 and Question 5.**

The challenge and the goal of the ML-enhanced AR navigation system of the thesis is to combine AR design ideas into a standalone mobile application, which will facilitate indoor guidance. This application will therefore not only perform effective AR navigation, but also it will retrain the system to identify changes in the environment. In the scope of this Continuous ML system, two parallel applications were created, one for the system administrators and one for the users-visitors of the target site. Figure 6 shows an overview of this intelligent system.

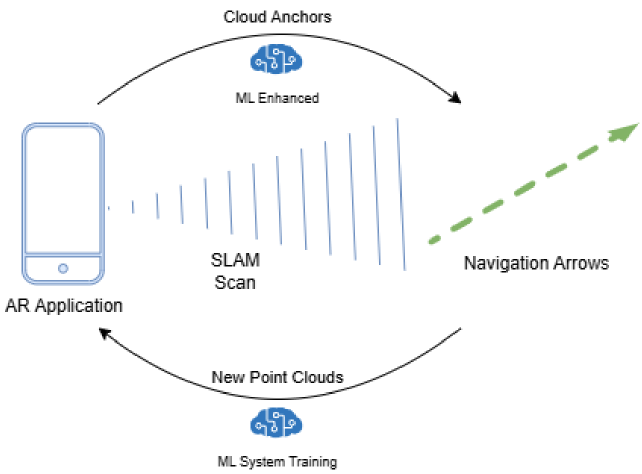

Figure 6: The overview of the ML-enhanced AR Navigation System. The system resolves the initially attached Cloud Anchors and records their point cloud again upon a user iteration. In the next navigation, the system resolves both initial and newly created Anchors.

3.1.3.3 AR gamified crowd management

This thesis presents an AR-based gamified system to manage crowd flow in exhibition areas, improving user engagement and accessibility [240]. Primary objectives:

Objectives	**Description**
Crowd Dynamics Modeling	Development of gamified AR solutions to manage crowd behavior in healthcare environments (e.g., hospitals, vaccination centers).
User Interaction	Interactive AR elements to guide individuals or groups safely and efficiently.
Scalability	Solutions must handle varying crowd sizes without compromising usability or performance.

Research questions answered: **Question 1, Question 2 and Question 5.**

The Gamified solution of the thesis that facilitates crowd management using AR in exhibition areas is defined by a set of proposed algorithms and efficient user engagement methods. The system is applied at an exhibition scenario. The predefined visitor path is divided into sections, which correspond to a room, in the proposed system methodology. Each section has a preset number of maximum simultaneous visitors. If this number is exceeded, the section will be too crowded. When the users enter the section by following the navigation path, the current section visitors are updated in real time. If a section gets too crowded (is getting close to the section limit), measures to control the incoming visitors flow are performed. These methods include AR games that engage the users to remain at this room, enhance their knowledge and have a pleasant time, as shown in Figure 7.

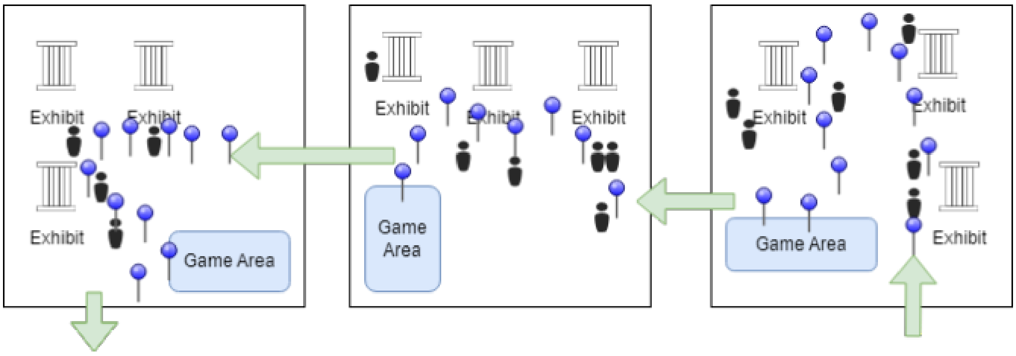

Figure 7: The overview of the AR Crowd Management system. Each room consists of: exhibits, game area, entrance and exit. Once a user enters the room, and after visiting the exhibits, he is being prompted to play an AR game, if the next room is too crowded. This progress is followed for every room of the exhibition.

3.1.4 Facilitating medical education through AR and CV

This thesis explores the combination of AR and Computer Vision technologies to create interactive educational tools that enhance medical learning and drug management, exemplified by a mobile platform for pharmaceutical substance recognition and visualization.

3.1.4.1 Mobile drug compound education platform

This thesis introduces a mobile AR application that combines Computer Vision and augmented visualization to identify pharmaceutical substances and display their molecular compounds for educational purposes [236]. To improve medical education, research in this area requires the following:

Objectives	**Description**
AR Interfaces	Integration of CV to identify pharmaceutical products through camera feeds, linking them with educational content.
CV Object Recognition	Benchmarking against dedicated medical-grade sensors to ensure accurate and reliable detection
User Engagement	Gamification elements to make the learning process engaging and memorable for medical professionals and patients

Research questions answered: **Question 1, Question 2 and Question 4.**

The proposed mobile AR application is a form of educational paradigm that facilitates in learning and appropriating molecular compounds in a three-dimensional figurative way. Designed to run on commodity devices with no extra static and expensive hardware, this prototype first recognizes the medicine box that is in front and then, displays the corresponding augmented information above.

The requirements outlined above form the foundation for the research contributions of this thesis. By addressing these needs, the proposed study aims to develop accessible, cost-effective, and intelligent solutions that enhance Remote Patient Monitoring.

3.2 Architecture

This section presents the Architectures of the developed systems within the scope of the Thesis. All systems share architectural principles and are designed with the best practices. To serve this purpose, a common architecture is designed, which aims at supporting entire mobile applications or part of existing applications, IoT device applications, web applications, configuration systems and cloud services. This common architecture consists of five primary components, which (or part of them) are applied to each solution. The elements are as follows:

- Mobile Component
- IoT Component
- Web Component
- Configurator Component
- Cloud Component

The Mobile Component serves as the end-user entry point of the systems and the primary output. The IoT Component represents applications developed for wearables, which retrieve and transmit sensor data either to the mobile device or to the cloud directly. The Web Component refers to online applications, like dashboards or real-time monitoring platforms. System configurations like area scanning are performed through the Configurator Component applications. Finally, the server side of this common architecture is represented via the Cloud Component.

3.2.1 Engaging users for increasing their physical and mental activity and RPM using AR, IoT and IMU technologies

This subsection outlines the design of the proposed solutions that integrate AR, IoT, and sensor technologies to support RPM and improve user engagement. By leveraging gamification, wearable devices, and mobile AR applications, the solutions aim to motivate users to adopt healthier lifestyles while enabling real-time health data collection and analysis. The designs focus on creating interactive and user-friendly systems that promote physical and cognitive activity, provide accessible RPM, and allow for seamless interaction between users and healthcare professionals.

3.2.1.1 Gamified AR and IoT platforms for remotely assessing physical activity

The system consists of three core components, which are analyzed in the following sections: (a) the AR game development framework that runs on mobile phones, (b) the smartwatch app that can be installed on WearOS smartwatches, and (c) the cloud platform and web app that provides remote game processing, user vital signs monitoring, and results visualization.

One of the main goals for the overall system architecture is to address the requirements for modularity and scalability to ensure possible future extensions. Therefore, the platform's components are designed based on the maximum possible simplicity, with clearly defined interfaces and abstraction layers, while maintaining performance and efficiency at high levels. The development tools and languages chosen and the way they have been used increase interoperability with third party services and allow future integration with other platforms. The components of the system that operate in the context of the mobile application are: (a) the menu manager and (b) the game controller. Wearable applications contain the (c) steps manager and (d) heart rate manager components, which take care of recording and broadcasting measurements to the mobile. Web applications include (e) the web results manager, which visualizes the results of the past game sessions, and (f) the web game manager, which sets the parameters for the games. The cloud platform component consists of storage, authentication, and synchronization controllers. Storage controllers are responsible for storing (g) health data,

(h) game scenarios, and (i) game results while (ia) authentication and (ib) synchronization controllers handle the user login status and data syncing accordingly. A complete component diagram is presented in Figure 8.

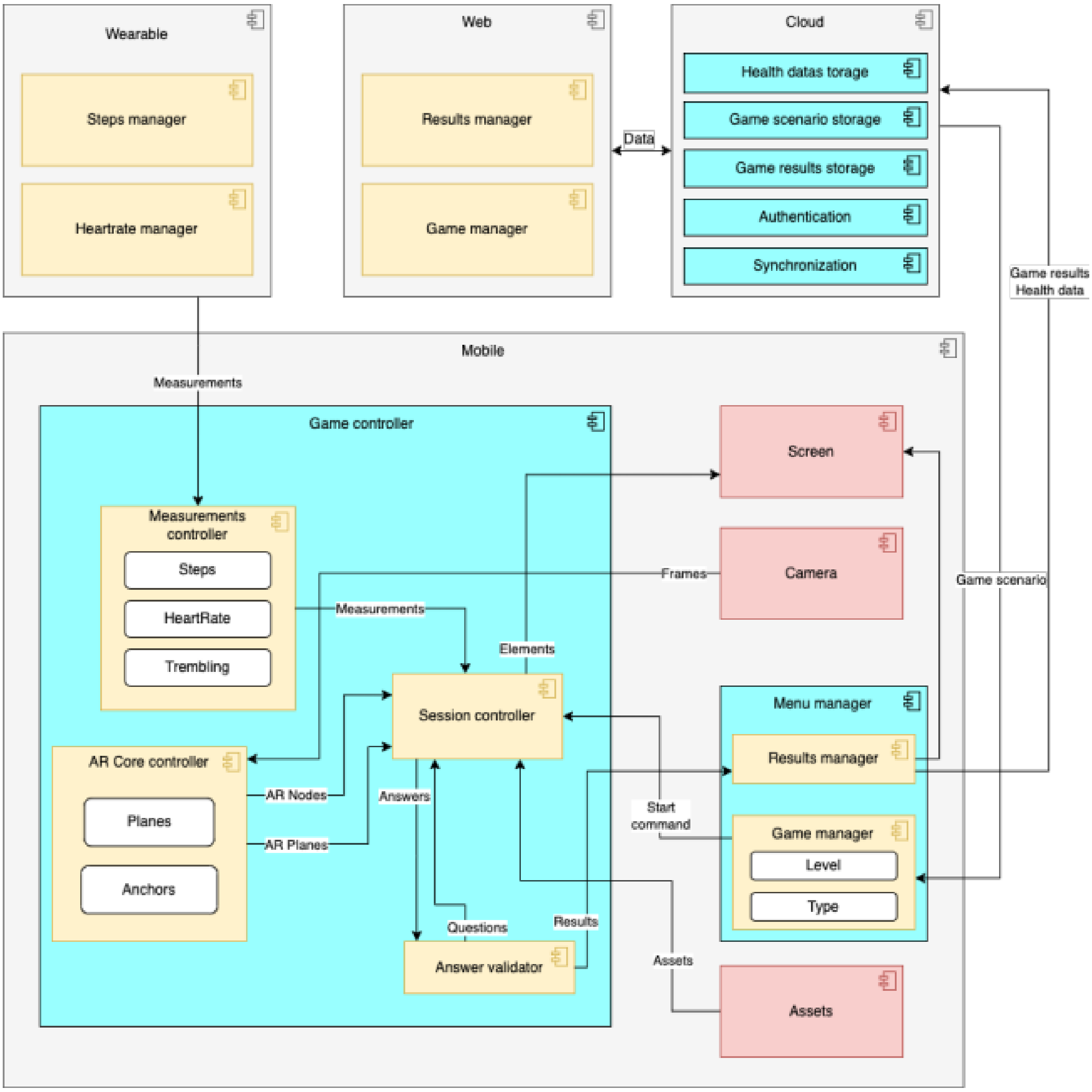

Figure 8: The architecture of the AR IoT Gamified platform consisting of Wearable, Web, Cloud and Mobile components. The Mobile Component handles AR and game sessions and transmits results along with data from the Wearable Component to the Cloud Component, to be displayed in the Web Component.

3.2.1.1.1 AR Game Development Framework—Mobile Application

The main functionalities of the game platform are implemented in the mobile application. The game displays to the user's screen the different quests and opens up a camera window, showing a view of the area in front. Using AR, the game options and actions are placed on different surfaces, asking the user to walk and interact with the virtual objects, as part of predefined game challenges.

All game quests, their types, and levels, can be selected by the user before the game or can be pre-configured by the healthcare professional through the web application in the context of a personalized care plan. Besides the game functionalities, the mobile app is also responsible for recording and analyzing the measurements supported by the system using the device's built-in sensors. These measurements mainly refer to hand trembling and user movement (exploiting the raw data from the accelerometer sensors), and after each successful or unsuccessful test, the score is calculated along with recorded health measurements. These results are shared to the professional's web app via the cloud.

3.2.1.1.2 Smartwatch Application

A core feature of the system is integration with wearables for capturing activity and biosignal measurements. The features are implemented through a smartwatch application that can be installed on the device that is paired with the smartphone. The app is launched automatically when a game session starts, and during the game, the smartwatch and the mobile applications communicate continuously using Bluetooth technology. The smartwatch records the heart rate, user movements, and steps, and relays the data to the mobile app, while at the same time, it indicates the results live on the watch screen.

3.2.1.1.3 Cloud Platform and Web Application

The web application is mainly an administrative environment that offers to the healthcare supervisor game customization options along with user result visualization. The end user can obtain a view of his/her game history and his/her rankings in the game leaderboards. The supervisor obtains a list of the user's game sessions and has access to game results, such as correct answers or mistakes, the score of each game, and session gameplay duration. Health-related data, such as steps, heart rate, and hand trembling, are also presented with visual lines and pie charts. These data can be classified and assessed, providing valuable information to the persons that are monitoring the users, or the users themselves. The supervisor has the ability to set the content, the types, and the difficulty of the various challenges for user tests, either generically for all games ot by personalizing the game of specific users. The data exchange between the mobile and web applications is performed through a serverless cloud platform. This set of microservices simplifies the deployment and instantiation of the platform and the game elements, ensuring the overall security, modularity, and scalability, and facilitating the system monitoring for smooth operations. It is responsible for storing game configuration, results, measurements, and for handling communication between web and mobile applications, acting as a midpoint.

3.2.1.2 Cloud-Enabled Gamification to Enhance Participation in Nature-Based Solutions

The proposed system adapts gamification techniques in order to motivate the users to complete specific goals by combining wearable devices like smartwatches, activity bands, mobile phones, and a sophisticated software architecture. Mobile devices can collect and send data to IoT systems, while the users receive all the information that is generated from these data by utilizing software solutions for better user's experience.

The system architecture is divided into Cloud, Web and two Mobile applications as presented in the component diagram in Figure 9. Each application contains components for manipulating the assets, managing content, configuring AR elements and other required procedures.

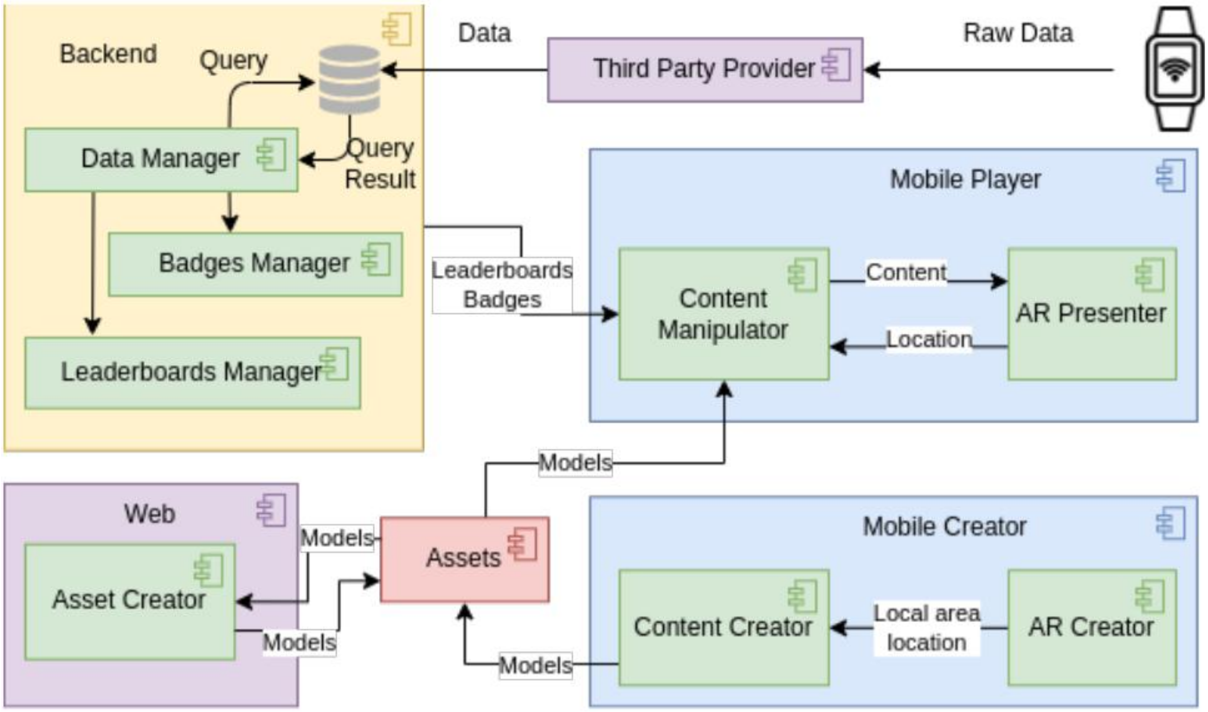

Figure 9: The architecture of the NBS AR-Gamification solution. The system consists of four primary components, the backend, the web, the mobile Creator and the mobile Player. Data are entered to the system via wearable devices.

3.2.1.3 Remote gait asymmetry detection

The platform consists of two main components: the Cloud Component and the Client Component. The Cloud Component runs on Cloud infrastructure and is responsible for handling user authentication and access, data storage and data transmission. The Client Component represents the prototype application that runs on the user's mobile phone. The primary objectives of this Component are the premeasurement configuration, measurement recording, results presentation and data export. The System Architecture is displayed in Figure 10.

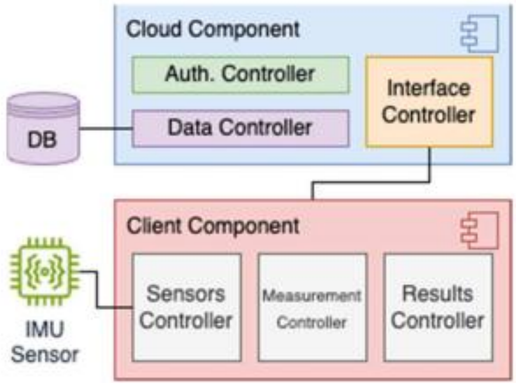

Figure 10: The system architecture of the mobile Gait Asymmetry Detection system incorporating mobile and cloud functionalities. The mobile side (Client Component) handles the onboard IMU sensor data and transmits them to the Cloud, before being stored to the database.

The Cloud Component consists of the Authentication Controller, which handles user creation, deletion and login, the Data Controller, which is responsible for storing and retrieving data from the database and the Interface Controller, which handles the communication between the Cloud and the Client components.

The Client Component includes the Sensors Controller, which configures and reads the data from the onboard sensors, the Measurement Controller, which initializes a new measurement and initiates the Sensors Controller data retrieval and the Results Controller, which handles the visualization of the recorded data. This controller also supports exporting the data. Moreover, the system includes a contacts system from which a physiotherapist can search and monitor patients. Hence, the results recorded by a patient can be immediately reviewed by the physiotherapists.

3.2.2 Assisting the impaired through handheld SLAM-based solutions

This subsection presents the design of assistive environments that utilize AR, SLAM, and cloud-based technologies to improve accessibility for individuals with impairments. The solutions include novel systems for museum exhibit recognition and obstacle detection, focusing on enhancing user interaction and safety in real-world scenarios. These designs emphasize hardware-independent approaches, ensuring that the solutions can be deployed using commodity mobile devices while maintaining adaptability and scalability in diverse environments.

3.2.2.1 Museum accessibility enhancement through AR cloud platforms

The key advantage of the Multitenant Cloud Platform for AR-based POI Resolution approach is that the operation of the cloud platform has been decoupled from the client applications in order to operate in a multitenant way. Hence, the platform can serve simultaneously multiple client projects adapting however the operational mode to each project for context-aware identification of anchors. The identification process can be further adapted to address dynamically changing needs during runtime based on the user profile, the condition of the area (e.g. highly crowded), interactivity with other participants and other special requirements. This dynamic operation allows for:

- dynamic allocation of the list of POIs to be identified,
- response with different metadata for each POIs based on the request query, and
- consolidation of alternative content to the POI according to the scenario (e.g. guidance of a sole visitor compared to the guidance of a group adolescents).

The architecture of the platform is presented in Figure 11. In conceptual level, it includes three main elements, a) the Persistence Layer, for storing all information regarding anchors and the assets related to them, b) the Services Layer where the business logic of the platform is implemented, and c) the Admin App for the definition of the anchors. The Admin App is used by the managers of the platform and dedicated users (e.g. the museum staff) and its main functionality is the initial identification and definition of the anchors in the area of interest. Through the app which is installed to the managers' mobile device the area is scanned using the camera, and the features of the foreground scene, of the surfaces, and of the objects are recorded in order to place the virtual anchors and store them in the database. The Anchors Manager component allows for editing the configuration and the metadata of the anchors as well as their ownership and access parameters so that they are available during runtime only to the specified audience. The Assets Manager component undertakes the process for uploading to the system and configuring the assets that will be in turn associated with the POIs. This is carried out through the Anchor2POI component where a many-to-many relationship is defined between anchors and POIs. Therefore, an anchor may represent different POIs according to the context, or a POI may span across multiple anchors. The Query Engine is the interface of the platform towards the client library and is responsible for the analysis of the client requests and for producing the list of anchors and related material (POIs and Assets) which will be used at any time from the mobile app.

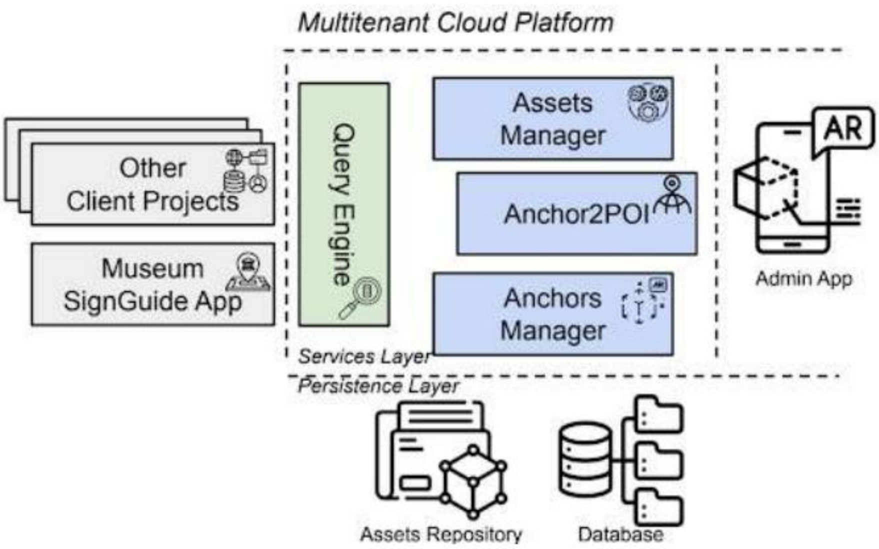

Figure 11: The multi-tenant AR Cloud Platform architecture. The platform includes a backend service and an admin mobile application. The backend service consists of a query engine and managers for Assets, Anchors and Anchors2POI. The platform connects with any mobile application and external assets repositories and databases.

3.2.2.2 SLAM-based obstacle detection

The proposed system, as a mobile application, consists of the following Components:

- Main Components: Main, Scene Updater, AR Manager, Depth Image Processor
- Decision Components: Steep Road Decider, Obstacle Decider
- Helpers: Sensor Helper, Sound Helper, Vibration Helper

Concerning the Helper Components, Sensor Helper Component reads data from the accelerometer and gyroscope, calculates the device orientation across the three axis and provides other components with the rotation information. The Sound Helper and Vibrator Helper Components are responsible for notifying the user. The first generates sound based on the current user direction, providing instructions for avoiding any type of obstacle, while the second produces vibrations based on the orientation of the device. Since the IMU sensor data includes a small number of errors or noise, to instantiate a vibration, more than one boundary violations need to occur in a short time frame.

The primary task of the AR Manager Component is the initialization and handling of the mobile AR engine as part of an application screen. It is responsible for recording the camera feed and displaying it to the user, along with a preview of the grid. It has continuous information about the device in the AR space. AR data from this component are traversed through to the Depth Image Processor Component, which generates depth information bound to each frame. During testing it was decided that in order to achieve the optimal obstacle detection performance, only one portion of the AR generated depth image is required. Specifically, area on the left and right sides of the recorded image are not part of the users path and, hence, obstacle detection in these locations of the image is redundant. Subsequently, the useful part of the image is divided into a 4x3 grid with averages for each cell being calculated. Data from the cells are traversed to the Decider Components.

The Steep Road Decider Component identifies steep paths or downhill cliffs in the camera image. It utilizes the lower row of the Depth Image Processor output to decide on whether there is downhill path upfront, on the left or on the right. This is achieved by comparing the average of each cell with a pre-defined limit. To make this Component immune to incorrect or inaccurate measurements, the same steep path must be detected more than once. Produces a result for each second and notifies the user one second after the identification of the first downhill cliff.

Following this architecture, the Obstacle Decider Component is utilized to detect objects. In this case the whole grid of Depth Image Processor is being used. If a cell average is lower than the pre-defined threshold, an obstacle is found. The value of the threshold differs for each row. This Component uses the same one second delay mechanism to prevent inaccurate measurements or spikes.

Finally, the Main Component defines the core of the application. It handles the proper data flow and all transactions between the rest of the Components and encapsulates the SceneUpdater Component, which manages the steady workflow of the execution of the algorithm. At each iteration, the orientation is calculated through the SensorHelper and the VibratorHelper is used when needed. Then, the ARManager produces data which are traversed through the Depth Image Processor to the Obstacle and Steep Road Deciders before notifying the user about any danger. The aforementioned Component Composition is demonstrated in Figure 12.

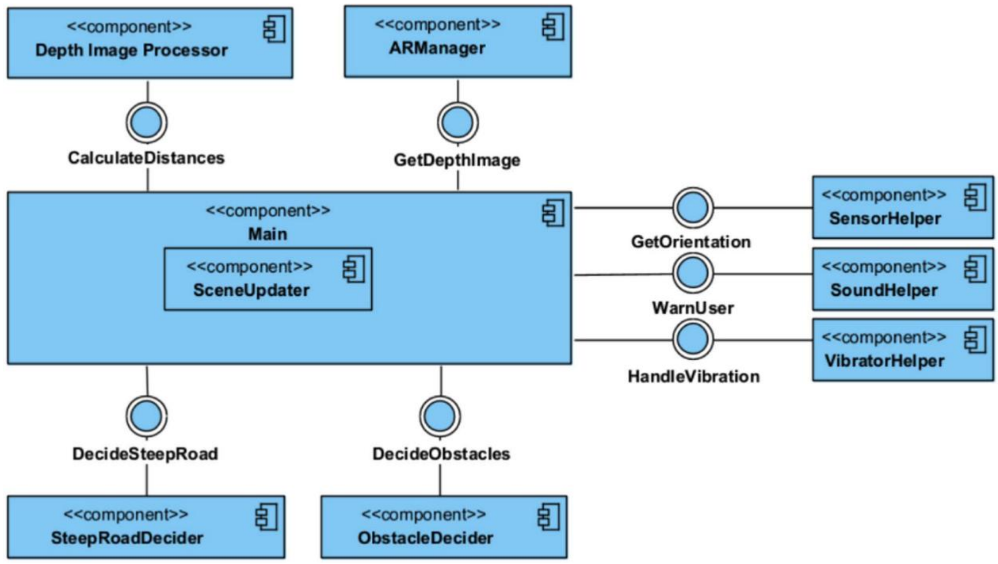

Figure 12: The Components of the System: The Main Component handles the system initiation and retrieves data from the Helper Components (Sensor, Sound, Vibration). ARManager Component handles the ongoing AR Session and provides data to the Depth Image Processor Component, which is responsible for extracting Depth-Maps. Finally, Steep Road Decider and Obstacle Decider Components utilize the produced Depth-Maps and produce the respective warnings through the Helpers.

3.2.3 Introducing location-aware mobile intelligent systems for navigation and localization

This subsection describes the design of intelligent, location-aware systems that enable advanced indoor navigation, crowd management, and localization capabilities in healthcare and public spaces. By employing AR, SLAM, and machine learning, these solutions aim to create accessible and efficient environments for users. The designs incorporate dynamic navigation algorithms, real-time crowd monitoring, and gamified elements to provide seamless and engaging user experiences in complex indoor spaces such as hospitals, museums, and exhibitions.

3.2.3.1 AR indoor navigation

The indoor AR navigation system consists of two main elements:

- **Hybrid AR Platform**: A unified framework which includes a client platform and requires integration of a client library. Is responsible for handling AR related information and consists of three modules: Creator Module, Administrator Module, Backend Service and a Query Engine.
- **Player Module:** a subsystem which can be integrated to any third-party mobile application.

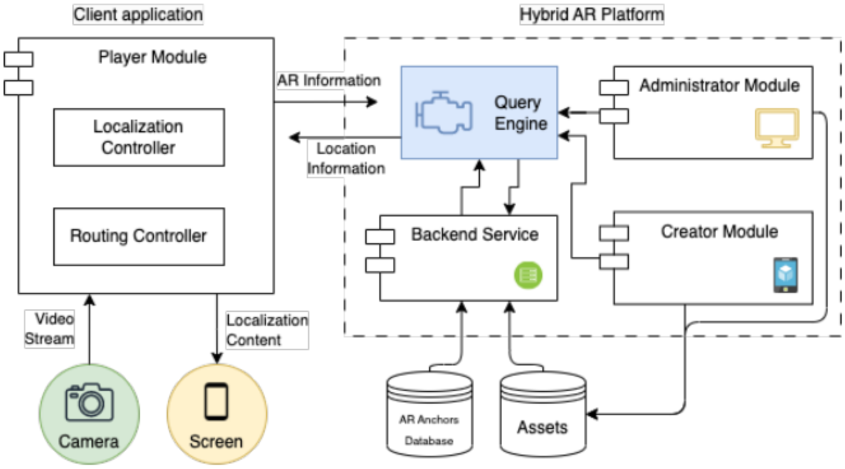

Figure 13: The Architecture of the AR navigation system. Video Stream is entered to the system from the camera feed. AR information is extracted and through the Hybrid AR platform is converted to location information, before being displayed to the screen.

Figure 13 demonstrates the architecture of the system, highlighting the Player Module and the Hybrid AR platform. Camera frames, along with IMU sensor data, are providing AR information to the Hybrid AR Platform. The platform integrates a Query Engine which performs queries of specific locations. Once a location is found, the related AR information is retrieved from the database and returned to the Screen of the Player Module. The system is trained via the Administrator and Creator modules of the Hybrid AR platform and data processing is performed by the Backend Service.

3.2.3.2 ML-enhanced AR localization

The system is divided into 3 entities, Administrator Application, User Application and Cloud Component. In order for the application to be considered functional, all three entities must be properly combined and interact with each other, taking into account the scalability of the system. The system architecture is shown in Figure 14.

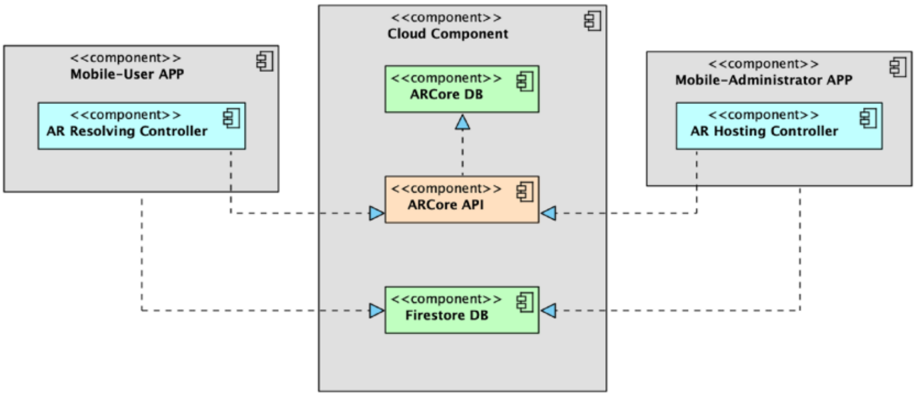

Figure 14: The ML-enhanced AR localization system architecture, consisting of three components: the Mobile-User App, the Cloud and the Mobile-Administrator components

Administrator Application

The system entity used by the site administration. It offers capabilities for: creating and editing Anchors, creating and editing Routes, defining the Anchor sequence of a Route and managing all other system aspects. Access is restricted to only authenticated users. The route creation process is achieved through this entity.

User Application

The User Application is offered to the visitors with no access restrictions. Destination options are displayed and, upon user selection, the navigation process starts. Based on a setting toggle, while navigating through the Route Anchors, the proposed CML algorithm is executed, generating and hosting Feature Maps for the already created route Anchors.

Back-end Application

For storing Route, Anchor and all other system information, a back-end system is required. For the purpose of this prototype, the serverless-Back-end As A Service—BaaS approach was selected which offers NoSQL database, storage and authentication with the use of a third party library.

3.2.3.3 AR gamified crowd management

The AR system manipulates AR content in the Cloud. It is responsible for interpreting the proposed algorithms and can be integrated with mobile applications in the form of an add-on package. It consists of a Client Module, an Administrator Module, a Backend Module, Database and Assets storage, as presented on Figure 2.

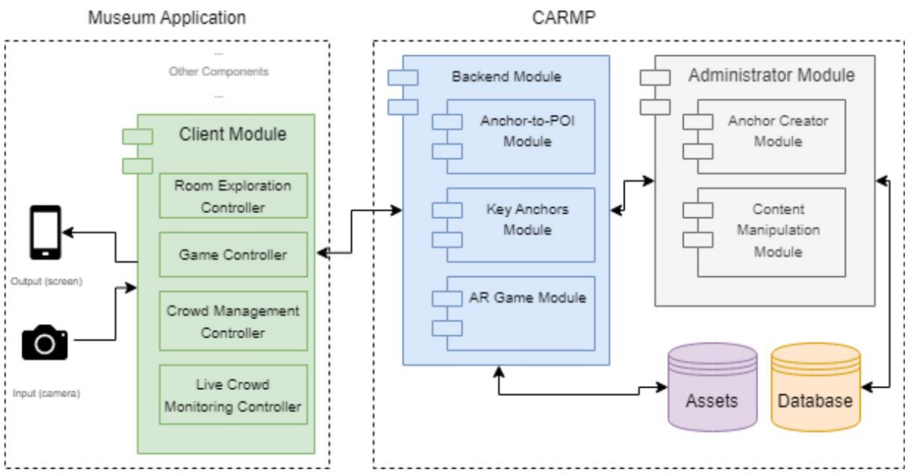

Figure 15: The architecture of the gamified AR crowd management system. The system consists of a Client, a Backend and an Administrator module. Client module runs the game on the visitors side, Administrator module manages the Anchor creation and content manipulation while both systems stay interconnected through the Backend module, which handles also the cloud Anchor management.

Client Module

The system's Client Module can be either a standalone application, or it can be attached to a museum's existing application, both by installing the respective add-on package. It is the application that is deployed to the users and handles all the human machine interaction. The Client's Room Exploration Controller and Crowd Management Controller are implementing specific exploration and flow algorithms. Client's Game Controller displays the AR games that delay the user and gives the user an indication of the current crowd status of the exhibition.

Administrator Module

The Administrator Module is a standalone application and is responsible for managing the AR functionality and manipulating the content. Access to this module is restricted to only the exhibition officials which are required to use it in order to train the system with the current configuration. It includes options to create, edit and delete sections, edit section full crowd, create, edit and delete Anchors, correlate anchors with Exhibits, create AR paths that are going to be used in the guidance and define the type and content of AR games.

Backend Module

The Backend of the system is in the form of serverless functions and communicates with the other modules using API calls. The Anchor-to-PoI Module is a subsystem responsible for identifying a location, correlating it with a certain exhibit and returning the exhibit data from the Database. Additionally, the Key Anchors Module identifies the current section based on the Routing algorithm's top-down approach and returns only the anchor data of the affected area while the AR Game Module loads the game data and Assets and returns it to the client for rendering. All Backend Module services require a continuous connection with the mobile application to retrieve SLAM data and return AR content.

3.2.4 Facilitating medical education through AR and CV

This subsection details the design of innovative educational systems that utilize AR and computer vision (CV) technologies to improve learning experiences in medical education. The proposed solutions focus on providing healthcare professionals and students with interactive tools to visualize complex medical concepts, such as pharmaceutical compounds and drug interactions. The designs emphasize accessibility and user engagement, ensuring that these applications can run on commodity mobile devices and deliver impactful, hands-on learning experiences.

3.2.4.1 Mobile drug compound education platform

Architecturally the AR pharmaceutical substances learning system is divided into three main components responsible for

- Text recognition
- Drug identification
- AR operations.

Camera and screen are the required components for the Text recognition and AR while PubChem and 3D Model databases provide assets to the Drug identifier and AR components.

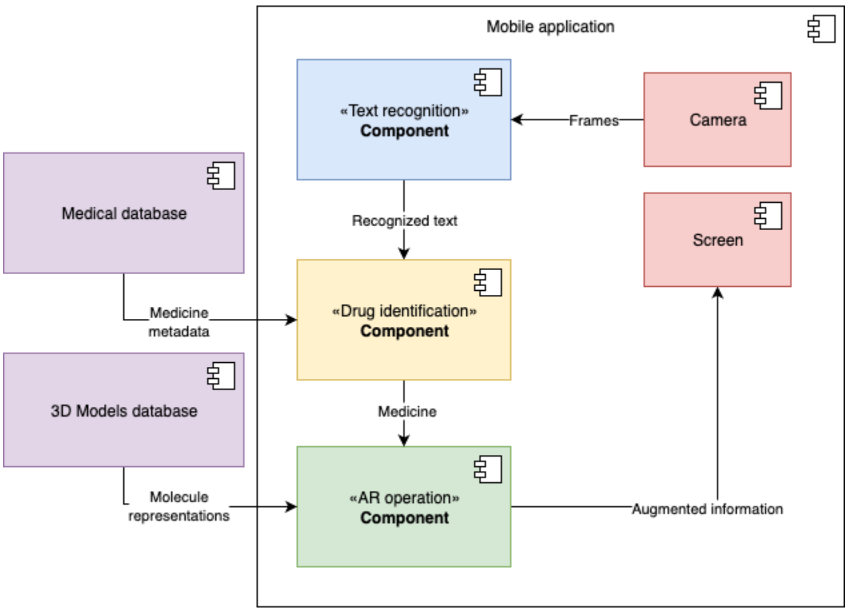

Figure 16: Component diagram of the AR pharmaceutical substances recognition system. The system consists of three primary components: the Text Recognition, Drug Identification and AR Operation components. The components access the device camera feed for AR and CV operations, identify drug boxes via CV, retrieve their chemical related data from specific databases and visualize the data via AR.

Text Recognition Component

This component is responsible for identifying text that is visible in camera. A frame from the camera feed is given as an input to the CV Text Recognition routine. This method returns sentences that are discovered along with their 2D screen coordinates. The result of each frame is provided as input to the Drug identifier component.

Drug Identifier Component

By analyzing the input text and comparing it with the database data, this component checks if a frame contains any text that refers to a medical substance. The analysis process is performed based on a Text Medicine Analysis algorithm (TMA) which analyses the input text and indicates any medicine-related information.

AR Operation Component

This component manipulates the AR library and visualizes the final result on the screen. It handles the drug metadata, extracts the compound and retrieves the correct model file. Additional information (retrieved from the database for each drug) is also provided to the user upon pressing the compound.

3.3 Implementation

The following subsections provide information about the implementation of the thesis proposed solutions. Such information is often divided into algorithmic and technical, giving insights on both the theoretical and practical conceptualization of the thesis study.

3.3.1 Engaging users for increasing their physical and mental activity and RPM using AR, IoT and IMU technologies

This subsection explores the technical and algorithmic details of the proposed solutions.

3.3.1.1 Gamified AR and IoT platforms for remotely assessing physical activity

This subsection delves into the implementation details of the gamified AR and IoT-enabled platform, which was designed to promote physical activity and enable real-time health monitoring. The focus here is on the technical aspects of creating AR-based exergames, wearable device integration, and cloud-enabled data storage for facilitating remote assessment.

3.3.1.1.1 AR implementation

The AR functionality, regarding the process of displaying and selecting answers, is implemented using the Google ARCore framework1. Although this framework was preferred due to the seamless integration with the Android ecosystem, there are other AR libraries that can achieve similar results. Apple's ARKit2 is a mobile framework that utilizes AR elements

[1] https://developers.google.com/ar

[2] https://developer.apple.com/augmented-reality

and presents similar results. However developing ARKit requires not only Apple test devices but also Apple computer infrastructure and special licenses, which lead to limitations, making development less flexible. AR.js3 is a lightweight library for AR on the web, which can be used in mobile devices by opening up a web browser window. Amazon Summerian4 and HoloKit5 are AR libraries that offer mobile device support, but their core AR elements when reaching the native device level are provided by ARCore and ARKit, depending on the platform.

The gamification experience is achieved through integration of Sceneform library-a 3D framework with a physically-based renderer that is optimized for mobile devices and and makes it easy for one to build augmented reality apps without requiring OpenGL. Sceneform provides ARCore functionality with Android interfaces and classes through an API. The ARCore utilizes the device's hardware, and by exploiting the library capabilities, offers an AR experience to the users. The UI of the game is presented through a fragment widget, which is provided by the library and is called an AR fragment. In this fragment, the view of the camera is rendered along with additional 3D objects that are generated by the AR and are called anchors. An anchor can generate its 3D model from an asset file or create a dynamic shape (rectangle, triangle, cube). In order for the anchors to remain steady in their positions, the plane app elements are used. Planes are basically surfaces within the scenes that allow the anchors, which are generated in this area, to remain motionless. The planes are invisible on the camera and are used only for classification and recognition. All of these UI elements, which are tailored in a Sceneform view and are initialized with AR fragments, consist of AR sessions. Callbacks for the environment changes and for the detection of anchors and planes are provided along with frame update listeners. When the session starts, the device records the camera input,

[3] https://github.com/AR-js-org/AR.js

[4] https://aws.amazon.com/sumerian

[5] https://holokit.io

recognizes objects and items that are in front, and classifies surfaces in order to generate planes. The session also stores information about all plane positions and provides functions to insert, update, or delete planes. The distance between a plane and the device can be calculated as well as the distance between two random planes. These parameters are exploited during game runtimes to create smooth experiences for the users and implement intuitive game controls as part of the real-world environment.

3.3.1.1.2 The game platform

The prototype of the proposed solution includes a framework for the development of serious AR games, quests, and challenges exploiting ready-to use game elements and functionalities. Each game consists of multiple series of questions with different types and difficulty levels, and for each level, different metrics and configurations are applied in order to realize the gamification concept for the users. The overall game configuration, which includes the various levels, challenges, and all operational parameters, can be defined through the web application from the healthcare professionals. It should be noted that these parameters can be personalized for each user and adapted during the runtime in order to tailor the overall solution and its operation to the specific usage scenario and the care plan requirements. At the same time, the use of metrics and configurations allows professionals to assess different parameters of users' physical and mental statuses, and to effectively motivate them towards specific activities in the context of a personalized care plan. The sets of questions that will be presented constitute a session and are based on the following types:

1. Text: a text question is presented on the top of the screen and the answers are displayed in the AR Scene. These answers can be numbers, such as the result of a mathematical expression or text, for knowledge-based scenarios.

2. Object: this question type throws three objects (e.g., animals, things, balls) in the scene and asks the user to identify and pick the correct animal that is requested.
3. Box: in this current question type, three boxes are presented in the area around the user. These boxes contain hidden answers and the user has to walk through them in order for the answer to be revealed.
4. Sort: a number of answers are thrown. These answers have ascending connections between each other and the user is called to put them into order. Usually, the style of this question refers to sorting numbers, days of week, months, etc.

3.3.1.1.3 Development Insights

Mobile and wearable applications are designed following the Android activity architecture, i.e., a set of self-contained screens that include all functionalities that they require and exchange messages with each other. The smartwatch app consists only of one activity that handles the sensor readings, displays the metrics on the screen, and broadcasts them to the mobile app. The mobile app, on the other hand, contains various activities that correspond to the (a) menu manager, (b) results manager, and (c) game controller. The web application is a single page app, which was developed using the Flutter framework. The backend operations are based on Firebase cloud services, especially the Firebase Realtime database. Through the database, the connection between the mobile and web apps is implemented, as well as the synchronization and storage of all system data.

The mobile application components (a, b) handle the system flow and manage the connections with the other applications. The menu manager (a) component consists of the results manager and the game manager modules. Results manager presents the results data of the games in grids, graphs, and tables, and these data are also stored to the cloud for remote access using the web app. Game manager sets the level and type of the game and sends the start command to the game controller. The game controller (b) component consists of the following modules: (a) the measurements controller, (b) the ARCore controller, (c) the answer validator, and (d) the session controller. The measurements controller calculates trembling, steps, and handles the connection with the smartwatch application. The ARCore controller manipulates the ARCore and Sceneform libraries and provides the modeled outputs to the game controller component. The session controller manages the operation of the game: it receives the start command, obtains the correct assets for the answers, initializes the ARCore controller, reads the measurements from the measurements controller, presents the game and the other elements on the screen, and finally handles the user interactions.

The smartwatch application components (c, d) communicate with the watch sensors and send the measurements to the mobile application via Bluetooth. On a technical level, the reading of the sensors and the communications with mobile are feasible with the use of the integrated Wear OS API.

The web application components (e, f) implement the workflow of the web interface. Initially, the web results manager (e) obtains the data stored by the mobile results manager component in the cloud and presents them to the supervisor. This element also undertakes the operations of setting the parameters, types, questions, and levels for upcoming games. Users can access their results in the results manager activity and view their progress, points, scores, performance etc. The users also have the option to share the results with their healthcare specialists or family and friends.

3.3.1.2 Cloud-Enabled Gamification to Enhance Participation in Nature-Based Solutions

The Cloud backend application is deployed on the Firebase environment and contains serverless functions and NoSQL databases. Badges Manager and Leaderboards Manager components are responsible for generating the user personified leaderboards and badges, managing all the user data retrieved from the database, as demonstrated in Figure 17 and Figure 18.

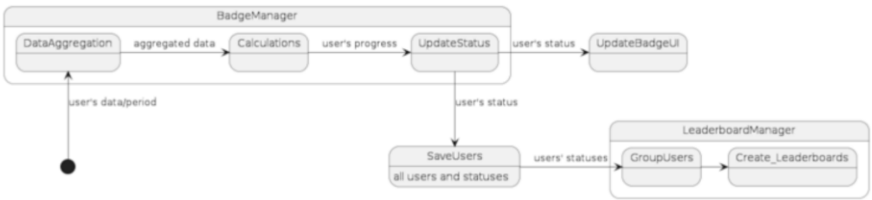

Figure 17: The Badge flow including Data Aggregation, Calculations, Status and UI updates, per users and user groups

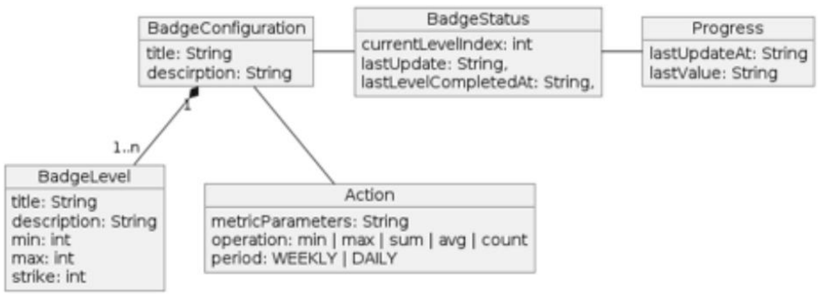

Figure 18: The data model of the Badges, including configuration, levels, action, status and progress.

The Web Application is available only to the system administration and manages the AR related content via the Asset Manager component. This component manages all content assets, the 3D models, vectors, images, and rich text that will later be presented to the user's application.

Two mobile applications are developed for the purpose of the prototype: Mobile Creator and Mobile Player. Mobile Creator is used only by the system administrators and handles the AR content creation flows. It is responsible for selecting the predefined locations that an AR anchor will be "dropped", defining the content of this anchor, and uploading the information to the

Cloud. Mobile Player is the end-user application that will be available to anyone who wants to visit the park. After authenticating the user, it retrieves health related data, badges, leaderboards and their appropriate AR anchors.

Based on SLAM, locations of the requested anchors are identified, and the results are visualized on the screen presenting a fascinating and comprehensive human-machine interaction experience.

3.3.1.2.1 Gamification Data Models and Operation

Modelling the gamification elements is a crucial task for the performance and for reusing scopes. A balance between simplicity and effectiveness on the model's design is used in order to perform both efficiency and reuse on those elements. In Fig. 3 b the badge model is illustrated as a composite object of three basic elements, the BadgeStatus, the BadgeConfiguration and the BadgeLevel. The BadgeConfiguration object contains the information about badge title, description, and levels. It also has actions to be used for computations. These actions include the metric parameters to be calculated (STEPS, DURATION, LOCATION and other), the period to gather the data (DAILY, WEEKLY) and the calculations to be performed on the collected data for analysing them. Every badge may contain more than one level in order to be marked as completed. Every level has a title, a description and a goal that is described by the min, max or strike elements. The min or the max value is required and specifies the minimum or maximum effort to be performed.

As an example, a goal could be described by setting the min value to 100.000 and metric parameter to STEPS which means that the user has to achieve at least 100.000 steps. If the strike element is set, then defines the times in a row that the user has to achieve a goal. A strike equal to 5 and a min equal to 6.000 for STEPS as the metric, means that the goal is 6.000 steps every day for 5 days in a row. As part of the operation, related queries are predefined and applied during runtime in order to perform efficient data retrieval.

The calculations are performed at certain times every day for all users and are represented in the model as Action objects. The objects include information about the type of data to be calculated, the queries, and the period (WEEKLY, DAILY) during which the data should be manipulated. In the next step, the computations are performed according to the definitions that are given by the BadgeLevel as described in the previous paragraph. If a Badge contains more than one level, the user must complete all the levels that compose the Badge, in order to set the Badge as completed.

Regarding the generation of the Leaderboards, the data are retrieved by queries that are predefined and are configured according to the data types and time periods. As a next step, the data are aggregated and grouped by gender and age category. Several classes are created in order to represent properly the users' achievements according to the different users' groups. Using this model, every user can view the charts related to achievements by his/her category.

3.3.1.2.2 The Augmented Reality Subsystem

AR for mobile devices is a technology that visualizes the required digital content without losing the user's sense of presence. For this demonstrative example the thesis is using Google's ARCore library with support for both iOS and Android. ARCore's Cloud Anchors API is utilized for applying SLAM techniques.

Anchors are hosted via the Mobile Creator application using Cloud Anchors hosting functionality. Three objects have been created, as illustrated in Figure 19, in order to proper display the visualized data at a precise location: GoogleCloudAnchor, LocalizedAnchor and VisualizedAnchor.

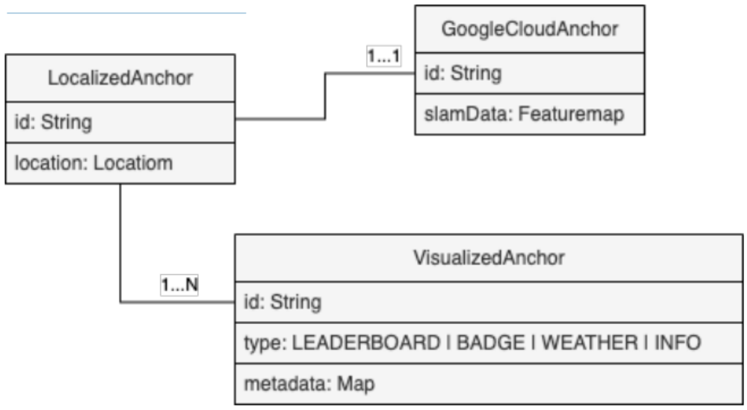

Figure 19: The AR Cloud Anchor model separating the location information of an Anchor from the visualized content, allowing, thus, the utilization of same visuals for multiple Anchors or the re-capture of the location of a visual.

GoogleCloudAnchor objects are stored at the Cloud Anchos API and contain the SLAM and feature map related information. LocalizedAnchors are responsible for matching GoogleCloudAnchors with coordinates and other location related metadata and, finally, VizualizedAnchors contain the content of each anchor that will be displayed to the end user. While LocalizedAnchors and GoogleCloudAnchors share a one-to-one relation, VizualizedAnchor objects are related with more than one LocalizedAnchors.

System administrators are responsible for localizing, attaching and hosting the anchors. The content that is contained in an Anchor is different per user and type, thus Anchors are separate from their displayed data. Mobile Creator and Web apps define which information will be presented at each anchor for each user. Mobile Player application uses ARCore Cloud Anchors anchor resolving functionality to download and localize the precise locations of the retrieved anchors. Appropriate information is retrieved from the cloud and visualized as an AR anchor on the screen.

3.3.1.3 Remote gait asymmetry detection

Monitoring gait asymmetry through accessible and cost-effective technologies is critical for rehabilitation scenarios. This subsection provides a technical overview of the proposed system, which utilizes commodity mobile devices and their built-in IMU sensors to detect gait patterns and asymmetries.

3.3.1.3.1 Measurement Methodology

Previous work has validated using smartphones in thigh pants pockets to assess gait events but with two phones, one on each leg [207]. To increase simplicity and ease of use, the thesis proposes an approach to detect gait events in real-time from the information acquired from the front side of the thigh with one mobile device. To be used first on one leg and then the other (in future studies non-paretic and paretic leg). The phone is positioned in the pants leg pocket with the screen facing upwards (back of the phone to the leg) to avoid involuntary actions from the leg touching the screen, and in a downward direction (head of the smartphone pointing down). This ensures that the sensors are aligned with mechanical axis of the lower limb, also called the Mikulicz line, drawn by connecting a point in the center of the femoral head to the center of the ankle [208]. A physiotherapist (male, 30 years old, 1,84 m) tested the proposed walking tasks in a straight line on a hard walkway without obstacles. Four gait strategies were performed: Normal, exaggerated, simulated paretic right leg and simulated paretic left leg. Two iterations for each gait strategy, one measure from the right and one from the left thigh pants pocket, and three trials to ensure consistency of the results [209]. The goal is to identify differences in gait event cycles between the two legs.

3.3.1.3.2 The “10-second” walk test

The walking task designed was a “10-second walk”, which is sufficient for gait events analysis in stroke patients [210], ensures ease of use in an in-home setting, and is based on an approximate 0,8 m/s community ambulator stroke survivor gait speed in the 10-Meter Walk

Test [211]. The application guides the patient on how to position the phone and notifies them when to start and finish each of the measurements by a vibration and sound alarm. Before each assessment, participants have a five-second window, after selecting “New activity recording”, to position the phone and prepare for the test. After the 10-second walk is finished, another vibration and sound alarm signal the end of the test, facilitating accurate assessment of the start and end of the measurement.

The phone sensors record accelerometer and gyroscope data which correspond to the instantaneous acceleration of the device in three-dimensional space and the instantaneous rotation around the device's three primary axes accordingly. The movements will be sampled at 20 Hz, based on the frequency of human gait movement (0,1 to 15 Hz) [212], 99% of the acceleration power in gait is concentrated below 15 Hz [213], and it has been determined that 20 Hz yields the most meaningful classification accuracies for gait smoothness evaluation [214]. Videos of the walking tasks were recorded for observational analysis and precision evaluation of the gait cycle recognition.

3.3.1.3.3 Technical implementation

To achieve the demanding requirements and at the same time decrease redundant development time, the system was chosen to be built using a Serverless Backend as A Service solution for the Cloud and a Cross-Platform Development Framework for the Client Component. Hence, Firebase and Flutter were chosen respectively. Firebase offers a set of tools which cover all the requirements for the Cloud Component without the need to deploy a Server. Moreover, it supports instant connection with the provided cloud services by offering dedicated plugins for mobile applications. Flutter is a Cross-Platform development framework by Google which uses a single code base and compiles applications that run on both Android and iOS. A specific

Flutter package for reading the onboard IMU sensor was utilized which allows for reading data at a pre-defined interval starting from 10ms.

3.3.2 Assisting the impaired through handheld SLAM-based solutions

The integration of handheld SLAM-based solutions offers significant potential for addressing accessibility challenges faced by individuals with impairments. This subsection examines the technical implementation of systems that leverage Simultaneous Localization and Mapping (SLAM) technologies to enhance navigation, obstacle detection, and exhibit recognition.

3.3.2.1 A Museum accessibility enhancement through AR cloud platforms

The integration of the platform with the client projects is performed through a library which is attached to the related client mobile applications during their. This library is responsible for capturing the video stream from the camera of the mobile device and the identification of the POIs by communicating with the cloud platform. The identification is performed in a hybrid fashion as follows:

- The client library makes a request to the cloud platform for a list of anchors to be identified providing contextual information (e.g. building, floor), the recently identified POIs and optionally user related information.
- The platform processes the request and responds with a list of anchors and their visual features.
- The features are used in the client library to identify locally the specific anchor in real-time from the video stream.

- When an anchor is identified, another request is performed to the platform in order to get the respective POI which is associated with the anchor, its metadata and the related content.

It should be noted that an anchor represents a specific spot in the area, which may represent one or more POIs, and according to the usage scenario and the request that will be performed, a different POI may be attached to this Anchor. Furthermore, the information and the metadata of the POI may also be dynamically produced and updated during runtime.

3.3.2.1.1 User application

The user application, through the integration of the client library for communication with the cloud platform, provides several innovative features with the most prominent being the ability to recognize an exhibit of the museum and have instant access to its information. Following the identification of the exhibit, and the presentation of the initial content, a set of questions is displayed, in both text and Sign Language. Furthermore, the user can have a look at photos related to the museum exhibitions or a specific question or answer.

The client library is responsible for performing the exhibit recognition on the mobile device. Once the appropriate button is selected, feed from the camera of the device pops up and indicates the user to point at an exhibit. At the same time in the background, the feature point recognition subsystem has already downloaded the features of the exhibits and continuously checks the current camera feed for patterns. When a frame contains sufficient features matching an anchor, the related POI content is displayed at the spot of the anchor. If the euclidean distance (in meters) between the Anchor and the device is less than 1.5 m, the user is considered to be close to the Anchor, resulting, thus, in the recognition of the corresponding exhibit.

While all AR related functionalities are exclusively integrated to the system, User Application acts also as the front-end of a sign language recognition and Virtual Avatar presentation processes. The user can either select one of the predefined questions or ask a question facing at the device's front camera. Answers are generated either in text or in sign language using prerecorded video or Virtual Avatar illustration. Needs to be mentioned, though, that backend implementations of the aforementioned processes are not developed as part of the thesis.

3.3.2.2 SLAM-based obstacle detection

SLAM-based obstacle detection systems have emerged as a promising avenue for improving navigation and accessibility for visually impaired individuals. This subsection details the technical implementation of a mobile application that leverages SLAM and depth estimation to detect and classify obstacles and cliffs in real time. The system introduces novel algorithms for depth map processing and obstacle segmentation, providing actionable feedback through haptic and audio cues.

3.3.2.2.1 Object Detection Algorithm

The functionality of the thesis system lies on detecting objects from depth maps retrieved via AR libraries. The proposed iterative algorithm is utilizing the Depth Estimation capabilities of AR resulting in depth-enabled camera images. The images are segmented into vertical and horizontal regions to which cliffs or obstacles are identified, followed by user audio guidance. The instructions guide the user to move the phone to face a region that does not contain obstacles. To ensure that the camera image is capturing the users path correctly, orientation constraints have been utilized, forcing the user to position the phone at the correct axis. This is achieved by continuously monitoring the device orientation and notifying the user via vibration feedback. The pseudo-code of the algorithm is shown in Figure 20 which uses text to describe certain actions, like “Update orientation angles”, “Warn user”, “Acquire depth image”.

```
while true do
  Update orientation angles
  if angleY > maxYangle or angleY < minYangle or |angleZ| > maxZangle then
    Warn user
    continue
  end if
  Acquire depth image
  if Depth switch is enabled then
    Visualize Depth-Map
  end if
  Split image into a 4 × 3 grid
  for i = 0 to 4 do
    for j = 0 to 3 do
      Calculate and show average depth in cell (i, j)
    end for
  end for
  for i = 0 to 4 do
    for j = 0 to 3 do
      if cell (i, j) contains an obstacle then
        Paint the text in cell (i, j) red
      else if i = 3 and cell (i, j) contains a steep path then
        Paint the text in cell (i, j) blue
      end if
    end for
  end for
  if any steep path was found then
    Warn user through sound
  else if any obstacle was found then
    Warn user through sound
  end if
end while
```

Figure 20: The pseudocode of the Object Detection Algorithm

The steps of the Object Detection Algorithm are demonstrated as follows:

1. The first step of each iteration is the check of the device orientation to discourage the user from holding the device at absurd viewing angles.
2. If the device is tilted outside the allowed limits, vibration and sound feedback is initiated and algorithm processes to the next iteration. This is crucial for the object recognition capabilities to be effective.

3. If the device is oriented towards the frontal space of the user, depth data is extracted from the image, generating a Depth-Map.
4. This map is converted to fit the device aspect ratio and divided into a grid of 4 rows and 3 columns. The average depth is calculated for each cell.
5. The next step concerns the identification of obstacles and downhill cliffs. For each cell, the average is compared to a pre-defined limit. If the average is less than the limit, it is considered that in this cell there is an existing obstacle. Respectively, for the downhill cliff identification, the last row of the grid is evaluated. If one of the cells of this row contains an average larger than the limit, it is considered to be a downhill cliff.
6. The last step is the user warning. The downhill cliff danger level is considered higher than the one of a possible obstacle and, hence, it is first checked if there is a downhill cliff, before checking for objects. The user is notified, via audio, about direction of the obstacle (center, left or right). If there are no obstacles, the algorithm is continued to the next iteration.

A more detailed view of the steps of the algorithm is illustrated in Figure 21, where a Flow Chart presents the corner cases of the iterative algorithm.

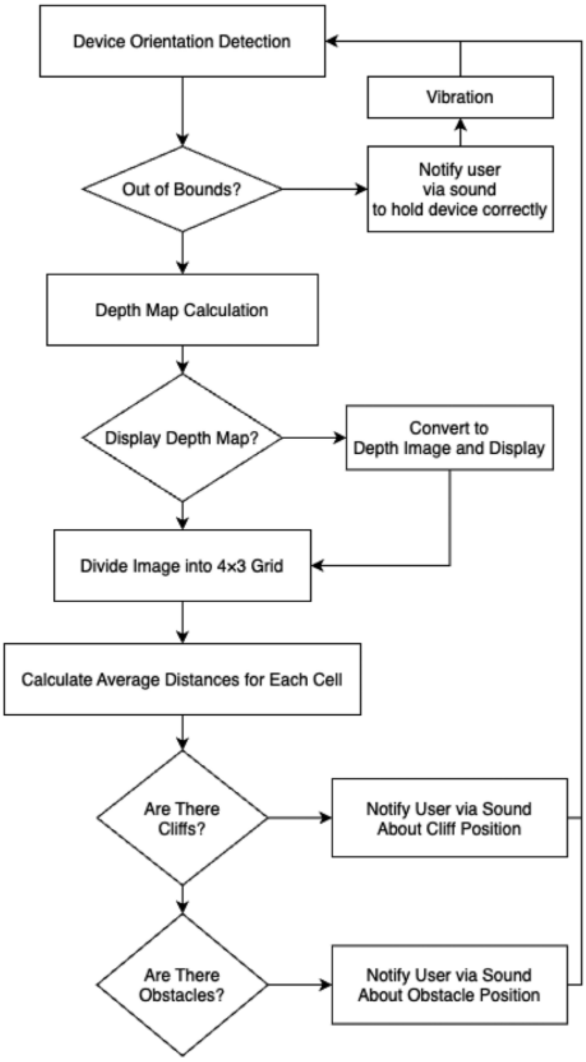

Figure 21: Flow Chart demonstrating the flow of the Object Detection Algorithm. It includes the basic cases: The orientation check, the Depth-Map extraction, the Cliff Detection and the Obstacle Detection. If the device is out of bounds or if there are cliffs or obstacles, the user is warned.

3.3.2.2.2 ARCore Depth API

The system was developed for commodity mobile devices. Android OS was selected for development simplicity and due to the available devices at the time. The aforementioned Components were implemented in Java and the AR depth functionalities are provided by the Google ARCore Depth API6. It employs a Depth-From-Motion Algorithm which generates

[6] According to the official Documentation, the ARCore Depth API achieves real-time Depth Estimation of a frontal scene of a mobile phone by using only its camera and IMU sensors. It allows AR applications to perceive and interact with the environment by extracting Depth-Maps in real time.

depth images, with each pixel representing the distance between a surface and the camera. By capturing multiple images from different points of view, comparing them, selectively applying ML methods and IMU data, this algorithm estimates the depth even without an onboard LiDAR or other depth-sensing sensor.

3.3.2.2.3 Depth Map Manipulation

The initial state of the extracted Depth-Map does not allow the efficient execution of the proposed algorithm. Hence, a processing of the depth image was performed. Initially, the image was fitted to the screen resolution, as the Depth-Map contains less pixels than the input image but maintains the same aspect ratio. Subsequently, the useful part of the image (the center of the image) is split to a 4x3 grid and via a distinct method, the average depth of each cell is calculated. The result of this method is an array with average distances. These averages are compared to predefined thresholds in order to define safe, or not safe, to walk cells.

3.3.3 Introducing location-aware mobile intelligent systems for navigation and localization

This subsection focuses on the development and application of intelligent, location-aware systems that utilize AR (Augmented Reality), SLAM (Simultaneous Localization and Mapping), and machine learning to provide navigation, localization, and crowd management solutions in healthcare and public environments.

3.3.3.1 AR indoor navigation

Building on the foundational concepts of positioning, routing, and navigation elements, the following subsection delves into the specific technical methodologies and implementation details that bring the AR Indoor Navigation system to life.

3.3.3.1.1 Positioning

To address the requirements of developing an AR navigation system, a set of algorithms and techniques, aiming at achieving indoor localization, performing efficient path planning and visualizing the guidance system are designed and implemented.

Indoor positioning & Key Anchors: A plausible observation arising from the Cloud Anchor functionality is the ability to achieve indoor positioning. If information about a location is related to an Anchor instance, the nearest Anchor identified by the device leads to the knowledge of the current position. Having multiple Anchors acting as reference points in a complex space, the term Key Anchors can be introduced. Such Anchors do not contain any visual information and are rather used to determine the device's position at the area.

Routing: Apart from identifying the device's position, Cloud Anchors can be used for a variety of other use cases. The proposed system prompts the user to follow an on-screen visualized path by using Anchors as route checkpoints. Routing entities are categorized as: ArPaths, ArRooms and ArRoutes. These entities are referring to relations between Anchors and locations, offering a stateof-the-art solution to the AR routing problem. An ArPath entity contains a list of Anchors that lead from a starting point to a gateway point. The order of the list defines the flow of the navigation. A gateway point is a special Anchor which includes references to the next ArPaths that begin from there. The ArRoom entity corresponds to a room of a building and includes ArPaths along with a set of additional satellite Anchors. Finally, the

ArRoute entity acts as a connecting pole between paths and indicates the final gateway of the route. Once a gateway is reached it is first checked if this is the final point. Otherwise, the first path of the ArRoute that is included in this gateway's next ArPaths is shown. This naive approach achieves a completely modular functionality which is tested under real scenarios showing successful results. Following the flow of this algorithm, a device can be navigated through different rooms, corridors and stories of the same building with the least required Cloud Anchors downloaded.

Navigation Elements Placement Algorithm: To overcome the possible long distance between two checkpoints, a series of helper Anchors is programmatically placed following the Navigation Elements Placement (NEP) algorithm. NEP locations are generated by

a) subtracting the first Anchor's transformation vector from the second to get the angle
b) getting the distance between these vectors
c) programmatically attaching an Anchor following the line of the subtracted angle every 0.2 meters, which is the interval until the distance is reached

3.3.3.1.2 Technical Implementation

All applications follow the object-oriented programming design principles and are built using Flutter, a cross-platform development environment. For AR services, ARCore platform and its Cloud Anchors environment is selected due to its ability of retrieving and sharing feature maps between both Android and iOS, resulting, thus, in seamless integration and interoperability.

The key advantage of the Hybrid AR Platform approach is that AR operations are separated from client applications, and are integrated into them through a software library.

The platform's Creator module is an application that hosts Anchors to the cloud and supplementary manages other system aspects and parameters. Hosting functionality is performed by initializing an AR session which allows Anchor placement at the front scene. Anchors are uploaded to the Cloud and their references along with other metadata are stored in the database. Additionally, this module modifies an Anchor's mesh position, location and orientation. An extended version of the Creator Module, without AR capabilities but with the ability to upload 3D model files and better manage the related content, is the Administrator module. This web application creates and manages instances of routing entities, modifies other administrative parameters that affect the workflow of the Query Engine and globally performs changes to all system configuration. A backend in AR applications was introduced to monitor physical activity via AR exergames [12]. The platform's Backend service is an extension of the aforementioned implementation, managing the storage of information regarding Anchors, Routes, Paths, Rooms and the assets related to them. The Query Engine acts as the interface of the platform. It is retrieving AR information and producing Localization material which is then transmitted to the Player Module.

The Player module can be integrated into any third-party application. The integrated Localization Controller searches for nearby Key Anchors and identifies the user's current position by communicating with the platform's Query Engine. At the same time, the Routing Controller interprets the routing algorithm starting from the current location towards the destination. Each time the Routing Controller retrieves new Anchors, they are transported to the AR screen in order to be visualized. In addition, this controller indicates that a user has either reached at a gateway or at a destination by returning this information to the Routing Controller.

3.3.3.2 ML-enhanced AR localization

Expanding on the foundational aspects of AR-based indoor navigation, the next subsection introduces the integration of machine learning to enhance AR localization, addressing adaptability and robustness in dynamic environments.

3.3.3.2.1 Continuous Machine Learning Algorithm

The integration of ML algorithms is necessary for the intelligent space learning function of the proposed system. Therefore, the Continuous Machine Learning (CML) approach was chosen. As mentioned, CML is concerned with how an application will improve its operation in the process of achieving its purpose and, in the current case, to improve the effectiveness of navigation during the execution of the application by the visitor. Initially, for the placement of an Anchor, a sufficient scan of the space with the camera is required to retrieve the best possible Feature Map of the Point Cloud, before uploading. When repositioning the device and the resolving process begins, the Feature Map must be mapped to the space captured by the camera at that moment and then the Anchor must be displayed with its 3D model at the predefined position. However, the process of matching these two Feature Maps might have a long process time, due to possible significant changes in the space, which might the currently recorded Feature Map quite a bit (wall color change, moving objects, obstacles in the camera, etc.).

The proposed platform introduces an CML oriented algorithm which is running each time an Anchor is trying to be resolved. This algorithm re-captures the Feature Map and creates a new Point Cloud with the goal of including possible environment changes. In the next download attempt of this particular Anchor, both the initial and the newly created Feature Maps are resolved. The application may have difficulty in matching the Feature Maps the first time these changes are detected. Subsequently, using data from newer training, it will produce a better temporal result. In the scenario of the Indoor Navigation, in which routes are displayed as a sequence of Cloud Anchors, each anchor is hosted via an initial training session. The visitor, then, resolves these Anchors and the final path is displayed. By using this algorithm, the visitor app is re-uploading navigation Anchors at their exact same spot and with the same 3D models while the users are following the navigation path.

The key advantage of this process is that the new Cloud Anchor is marked with a Feature Map from the user's camera recording at that moment, so it corresponds to the most recent form of the environment. In this way, each main navigation point (Checkpoint) can have several Cloud Anchors with different Feature Maps, each corresponding to the same location with minor changes in the environment. It is important to note that during the process of matching the Feature Maps, the application does not try to fetch all Cloud Anchors of a Checkpoint, but only a portion of them, due to hardware limitations of the mobile devices. The Anchors that will be resolved are selected according to a metric which is based on sorting the Anchors by their success rate. This metric is determined by a set of weights, which are assigned to each Cloud Anchor and increase when that Anchor is detected. Automatically, as can be easily understood, Cloud Anchors with zero or low weights are considered as improperly placed and are deleted from the system after a defined period. The key contribution of implementing this algorithm into an indoor AR navigation system is the combination of ML with AR for detecting minor changes in the environment. No algorithm is executed to alter AR operation data, but an additional layer of AI is added on top of the AR layer to optimize the processes. Although this approach probably increases the complexity of the system and requires more computational resources, it optimizes the system operation and gives a direction towards solving the SLAM data environment variation problem.

3.3.3.2.2 Technical Implementation

The prototype, which serves the purpose of the system evaluation tests, was developed in Flutter cross-platform framework, for the simplicity and the acceleration of the research. For the BaaS module, Firebase was chosen due to the scalability and the seamless Flutter multi-platform integration it offers. Cloud Firestore, a document-based database is used for storing the Route, Anchor, Path and User data while 3D models are saved in Firebase Storage. Concerning the AR, the Google ARCore framework was chosen, due to the aforementioned reasons, via the "arflutter-plugin" Flutter library, which wraps Android and iOS ARCore implementations into an autonomous Flutter interface-without requiring development in platform code. The ARCore SDKs provide APIs for all the key AR Features, such as motion tracking, environment understanding, and light estimation.

The primary ARCore service the thesis utilizes is the ARCore Cloud Anchors which handles the image capturing process, Point Cloud detection, Feature Map extraction and Feature Map upload to the Google Cloud [22]. After an Anchor location is uploaded a unique Cloud Anchor ID is generated [54]. This ID can afterwards be provided to the API, along with the camera feed, to resolve that particular Anchor. This functionality is used by the system in both User and Administrator applications and the Feature Maps that are generated are shared between both development platforms. Hence, an Anchor uploaded by an iOS device can be resolved by an Android and vice versa.

3.3.3.2.3 Cloud Anchor Upload Process

At first, a specific screen with embedded camera feed is displayed to the user, displaying the identified Feature Points and AR Planes of the frontal environment as the user walks through. Once the user selects (taps) a position, a local Anchor is attached and a 3D model is displayed at that position. Via a specific button, the user is able to begin the Anchor upload process to the ARCore cloud service. When the upload process finishes, a unique ID (cloud-anchor-ID) is returned to the user which corresponds to the just uploaded Cloud Anchor. This ID is stored, along with other Anchor related data (display name, building, floor, approximate coordinates) at the system database and will be latter used to resolve the Anchor.

3.3.3.2.4 Cloud Anchors Resolve Process

A screen with an embedded camera feed is displayed while the required Cloud Anchor IDs are fetched from the system database. By providing the IDs to the ARCore library, the Resolve Process begins in the background, while the user is scanning the area. The Feature Maps of the current area scan are compared to the ones that are fetched from the Cloud Anchors API and, if a pattern is identified, a new Anchor with coordinates referring to the initial Anchor location is returned.

In the proposed system, the upload process is performed from both the Administrator and the Client applications, the first for the initial route recording while the second for serving this novel CML approach. Regarding the CML implementation, multiple Cloud Anchor IDs are uploaded for a single route way point, the primary one created by the Administrator Application and all others generated by user navigation sessions. Particularly, when the user iterates through the navigation way points, once a point is resolved, it is instantly re uploaded as a new Anchor with the same coordinates, but with the current (updated) Feature Map. A metric called "valuation" is attached to the Anchor model, and will later be updated based on the success-rate of this Anchor.

The resolve process is the core functionality of the AR Navigation approach and is mainly used by the Client Application, although the Administrator application also supports it for development and internal testing. While navigating through the way points, the system resolves all (primary and CML generated) Cloud Anchors for that point simultaneously. If any of these Anchors is resolved, the process is killed. The appropriate visualization is rendered and the "valuation" metric for that Anchor is updated. Due to the ARCore limitation of only 40 simultaneous Cloud Anchor resolve attempts, the to-be-resolved Anchors are limited to the ones that have the best "valuation" score until the aforementioned limitation is reached.

3.3.3.3 AR gamified crowd management

The visitors path of the exhibition is divided into sections corresponding to a room. Each section has a preset number of maximum simultaneous visitors. If this number is exceeded, the section will be too crowded. When the users enter the section by following the navigation path, the current section visitors are updated in real time. If a section gets too crowded (is getting close to the section limit), measures to control the incoming visitors flow are performed. Three algorithms have been developed to facilitate routing, crowd management and visitor section exploration.

3.3.3.3.1 Section Exploration

The Section Exploration algorithm is responsible for displaying content related to the exhibits along with on-screen augmented guidance. It is utilizing SLAM and Cloud functionality to identify the area, locate the reference points and identify the exhibits. Then, after retrieving the exhibit data, virtual content is displayed either on the AR screen or as information text on the user’s mobile phone.

3.3.3.3.2 Flow Management

This is the primary algorithm of the system which handles the flow of the visitors. The algorithm requires that the visitors are always using their mobile phone to navigate through the exhibition. The system is initialized, and SLAM is executed to identify the current section while prompting the user to walk in. Once the section is identified, a counter is increased, notifying in real time that this section has one more person inside. The section Exploration algorithm is then executed, navigating the user through the exhibits via on-screen augmented guidance. When the user reaches the end of the exhibition path, the next section's crowd state is checked. If the next section is too crowded, the user is prompted to play games correlated to the current section exhibits. The user continues to play the games while the next section is still crowded. If the next section is getting empty, the game will stop and a prompt notification to continue the exhibition will popup. The current section counter is decreased while the user walks towards the next section. This process is repeated for all sections of the exhibition as demonstrated in the following pseudocode:

```
i ← 0
sections ← getSections()
while i ≤ sections.length -1 do
    section ← sections[i]
    slamResult ← section.getAnchors()
    if slamResult.hasError() then
        exit()
    end if
    increaseCurrentSectionCurrentCrowd()
    saveEntryTime()
    sectionExploration()
    if i ≤ sections.length -1 then
        nextSection ← sections[i + 1]
        while nextsection.currentCrowd >= nextsection.maxCrowd do
            busyUser(sections[i])
        end while
        decreaseCurrentsectionCurrentCrowd()
        saveExitTime()
    end if
    i ← i + 1
end while
```

3.3.3.3.3 Gamification

The *busyUser* method is the method that is delaying the visitor while waiting for the next section to be less crowded. A set of AR games correlated with the section exhibits are played by the visitor using only a mobile device. Once the visitor is finished playing, a next game will pop up or a prompt to continue to the exhibition, based on the crowd state of the next section.

3.3.3.3.4 Technical Implementation

The mobile applications of the system are implemented using Flutter. The AR functionality is integrated using ARCore Library by Google. A specialized Flutter package wraps the ARCore library for Android and iOS providing a single interface for communicating with the AR platform. The cloud applications and the rest of the system is developed using Firebase, an ecosystem of database, storage, authentication and serverless functions which provides easy adoption, fast integration and reliability.

3.3.4 Facilitating medical education through AR and CV

This subsection explores the integration of AR and Computer Vision technologies to create interactive tools that enhance learning experiences for healthcare professionals and students.

3.3.4.1 Mobile drug compound education platform

The system is designed to run on commodity devices. For the medicine box recognition, Google's ML Kit Text Recognition[7] framework is used, combined with data retrieved from the

[7] Google MLKit: https://developers.google.com/ml-kit/vision/text-recognition/v2

PubChem8 database. Visualization of augmented information (medicine and its molecule compound) is performed using the Google ARCore library. To achieve interoperability and user ease of access the application was implemented in Flutter. Camera, screen and IMU sensors are the only device's hardware required while connection with external resources is established for medicine and 3D models database access.

3.3.4.1.1 Text Recognition

Text recognition utilizes the camera feed used to provide the AR functionality. Images from the feed are provided to the Text Recognition Component which identifies text strings along with their 2D screen coordinates.

3.3.4.1.2 Drug Identifier

The recognized text values are provided to the newly created Text Medicine Analysis (TMA) algorithm. The algorithm analyses the input text and indicates any medicine-related information. The steps performed by the algorithm are the following:

1. Performs text pre-processing (lowercase, trim, delimit)
2. Gathers data from the database and search for relations
3. Retrieves and returns the drug that corresponds to the text, if any. The key value of the search can be either the name of the medicine or the name of the drug (e.g. paracetamol, aspirin)
4. Identifies the location of the text and also return the on-screen 2D coordinates.

[8] PubChem is the world's largest collection of freely accessible chemical information, including chemical and physical properties, biological activities, safety and toxicity information, patents, literature citations and others. https://pubchem.ncbi.nlm.nih.gov/

Once the drug is found by the TMA algorithm, the returned result is parsed as input in the ARCore component. This result contains the 3D model of the compound, the title and all related information of the drug retrieved from the PubChem database in a json format.

3.3.4.1.3 AR Operations

The molecule compound 3D model of a selected drug is downloaded in a .glb file format. Based on the 2D dimensions of the text, the center of the text is calculated with the top left corner of the screen acting as the start of the axis. A specialized routine converts the 2D screen coordinates to 3D coordinates in the AR frontal space. The model is then presented at the newly created 3D location. Model's size and orientation are pre-configured in order to maintain a common pattern. An additional drug information screen is accessible through the AR session visualizing the PubChem retrieved data based on user interaction.

4 Results

This section provides information about the results of the conducted study, showcasing the developed systems in practice and providing evaluation insights.

4.1 In practice

The following subsections present how the proposed approaches and technologies can be applied in real-world healthcare scenarios, demonstrating their practical relevance and potential.

4.1.1 Engaging users for increasing their physical and mental activity and RPM using AR, IoT and IMU technologies

This subsection presents the practical implementation and outcomes of the proposed systems that leverage AR, IoT, and sensor technologies to engage users in physical and cognitive activities while enabling remote patient monitoring. The solutions are designed to run on commodity mobile devices, ensuring accessibility, affordability, and ease of use. Below, the individual components and their applications are highlighted through real-world use cases and prototypes.

4.1.1.1 Gamified AR and IoT platforms for remotely assessing physical activity

The game session begins when the menu manager provides the base navigation of the app and also sets the preferred difficulty level and quest type options. This configuration is sent to the game controller in order to initiate the session in the app UI by presenting the AR activity. Based on the quest type, the appropriate questions and possible required assets are loaded to the memory. The measurements controller is initialized and establishes the connection with the smartwatch app (if the watch is paired with the phone). It also initializes the phone's accelerometer sensor, for detecting hand trembling, and a step counter sensor that is going to be used if the watch's sensor is not available. The game iterates through all the different challenges of the quest. A challenge (e.g., a question) is displayed as text at the top of the screen and the answers are rendered on the AR fragment. Each answer is modeled as an anchor that is placed on a plane that is identified in the area around the user.

4.1.1.1.1 Responses Data

When the user taps on an answer, this answer is stored and the whole iteration proceeds to the next question. In addition to storing the result of the question, metrics that were recorded during the session are stored. These metrics include:

- Duration: the time that the user needed to find, catch, decline, or accept the answer.
- Miss hits: the failed attempts of catching an answer (due to long distance from the object or failure in aiming at the object).
- Incomplete sessions: sessions that are terminated by the user before finishing.
- Steps: the steps that are counted either by the watch or by the phone sensor.
- Heart rate: full heart rate series as recorded by the watch, along with min/max/avg indications.
- Hand trembling: using the accelerometer sensor of the phone, the hand trembling can be detected and classified either in a waveform format or in classification categories, based on the accelerations that are detected from the sensor.

- FPS and battery drain: FPS are calculated using the frame update listener of the AR fragment and exported in min/max/average. Battery drain is the delta of the current battery's percentage.

4.1.1.1.2 Mobile Application

The game offers an AR experience to the user combined with real time steps, heart rate, and trembling indicators. After picking a set of questions, level, and type (can be pre-defined for the user by his doctor), the AR game session starts. The goal of the game is to walk around the area in front and try to catch the virtual objects presented in the screen. Types of the AR objects are defined by the question type of the current game quest. There are currently four game quests supported. The gameplay for each question type that is currently supported among with snapshots of the IoT wearable app is shown in Figure 22. The device that this example was running on was Huawei P20 Lite-ANE LX1 (CPU: 2.36 GHz, RAM: 4 GB, 16 MP Camera).

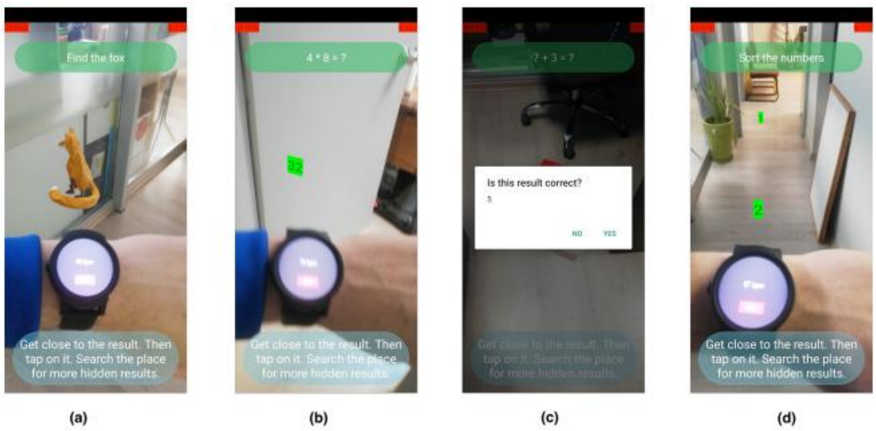

Figure 22: The main game quests: (a) object question, (b) text question, (c) box question, and

Type (a) refers to questions that display a 3D model as the object of the quest and the user is asked to identify the requested object and tap on it. Answers presented in free text are displayed as depicted in (b). Type (c) refers to box-type questions, where the user has to tap on the box for the possible answer to be revealed. Finally, in type (d), the user has to pick the displayed answers in a certain order. The positive effect of the gameplay is that the user will have to walk around in order to catch the answers and continue in the game.

The context of questions can be defined based on general interests of the user, resulting in an exergame that increases his/her physical activity and also keeps the user mentally motivated by being close to his/her interests.

4.1.1.1.3 Web Application & Cloud Platform

A core part of the system is the cloud platform for the storage of the game scenarios and the results, as well as the web app, as it is the platforms endpoint for healthcare professionals. Figure 23,Figure 24 and Figure 25 illustrate the main functionalities of the web app. The app focuses on the visualization of the results and the rankings, which are presented, based on a point system that classifies the users' results in tiers. In the prototype implementation of the game scenario, three tiers are proposed; namely silver, gold, diamond, and challenger. Heart rate and trembling are presented in the answer's screen following the format of line and pie charts. The rest of the metrics are also presented in the dashboard.

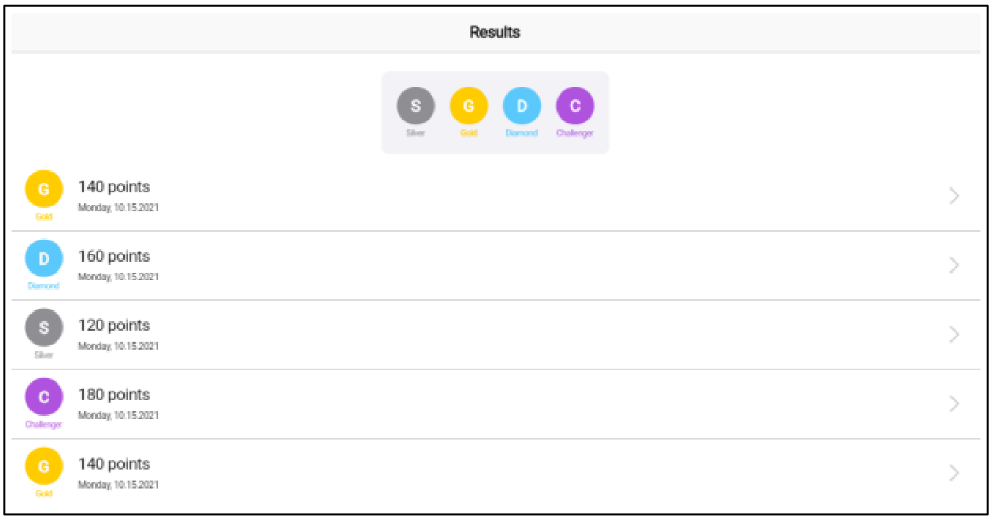

Figure 23: The Web Application dashboard.

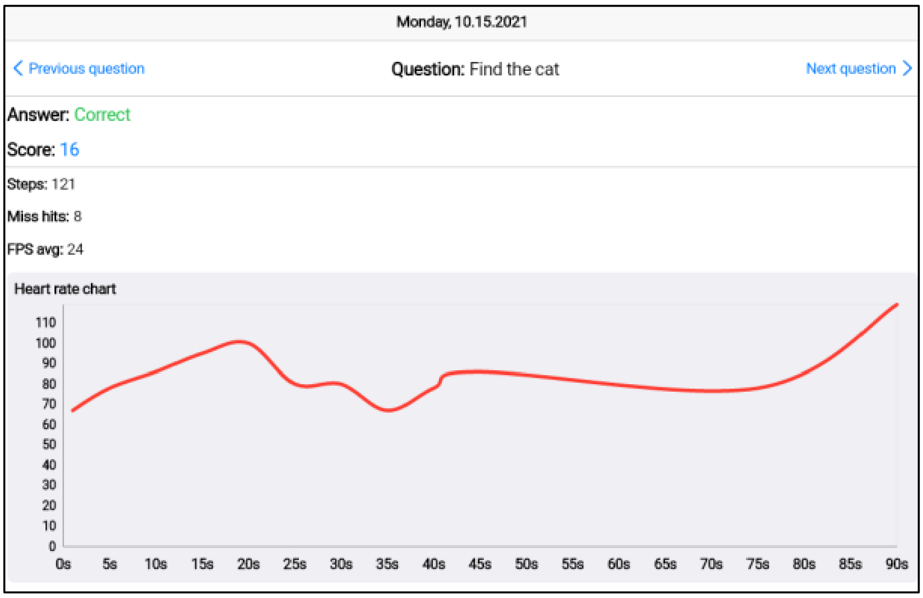

Figure 24: The question results screen showing score, steps, miss hits, FPS and heart rate charts.

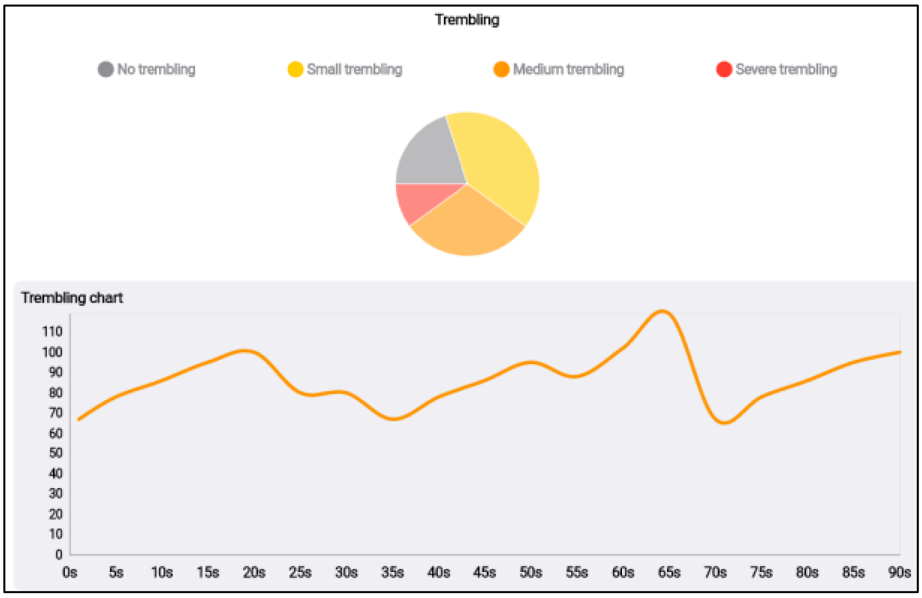

Figure 25: The trembling screen showing the four trembling stages, from No Trembling to Severe .

4.1.1.2 Cloud-Enabled Gamification to Enhance Participation in Nature-Based Solutions

The developed prototype was tested in real-world usage scenarios by introducing AR objects for both Location-based and User-specific data categories. The precise locations of the objects were defined by the Creator application while the data are presented dynamically. Internal validation activities took place in the context of the project which focused on the technical aspects. The usability and the overall effectiveness will be assessed in pilot deployments in three cities which implemented NBS. The prototype will be available to the project participants and it is currently closed source, however after the assessment, the delivery of a public version will be considered.

For Location-Based AR objects, indicators providing places for outdoor gym as well as weather-related information are displayed, as presented in Figure 26. These objects have a location-based content, meaning that they are visible to all users and their goal is to notify, inform and help. Concerning the User-specific information, as demonstrated in Figure 27, data from leaderboards and badges are generated and visualized. The leaderboard ranks the current user compared to all others (anonymously) while the user's current badge can also be found in the park. Although the location of such objects is predefined by the creator, the content is different for each user.

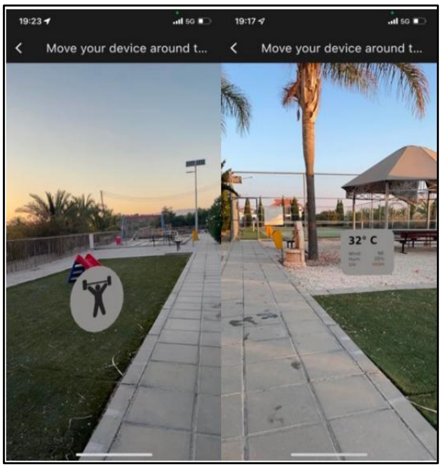

Figure 26: Snapshots from the NBS AR system in practice. This example shows Anchors that indicate workout locations (left) and weather information (right).

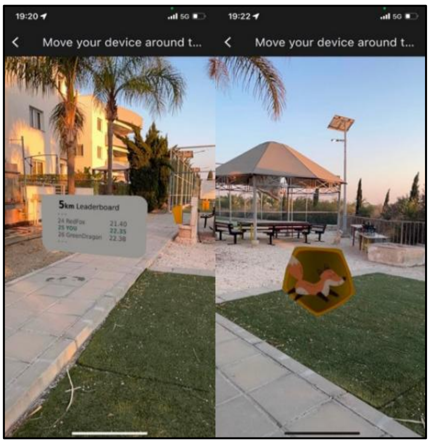

Figure 27: Snapshots from the NBS AR system gamification AR elements. Leaderboards Anchors (left) and Badges Anchors (right) are positioned at the NBS site.

4.1.1.3 Remote gait asymmetry detection

The proposed thesis system is implemented and tested under real conditions. Testing scenarios were executed and results from both the device sensors and external resources (for validation) were recorded. To simulate gait cycle asymmetries, the collaborating physiotherapist performed tests which included walking with inconsistent gait cycles. IMU data were recorded for both legs by inserting the phone into the respective pocket. Sampling rate was set to 250ms. Four testing scenarios took place with three testing sessions for each scenario: Normal Walking, Exaggerated Walking, Paretic Left Leg, Paretic Right Leg resulting in 12 tests in total. Each session requires inserting the phone in both pockets and executing two 10- second walks.

Figure 28 demonstrates snapshots from the system in practice: the correct phone insertion procedure (a), the Normal Walking test (b), the Paretic Right test (c), and the results (d) are presented.

Figure 28: The gait Asymmetry Detection in practice: the correct phone insertion procedure (a), the Normal Walking test (b), the Paretic Right test (c), and the results (d).

The system extracts IMU sensor data as a list of values of three-dimensional space. These data are presented in the form of line charts on the phone screen and can be exported as .csv files. From the related reference to the literature [215] gait cycles are defined as the steep dives or elevations of the IMU line. Hence, the identification of local extremes equals the identification of a gait cycle. The proposed platform identifies the gait cycle durations and highlights the inconsistencies between the values of each leg. Indicative results are demonstrated from the Paretic Right Leg scenario in Figure 29. If the instructions are followed correctly and the phone is facing downwards with the screen outwards, the X axis of the Gyroscope provides the valuable data.

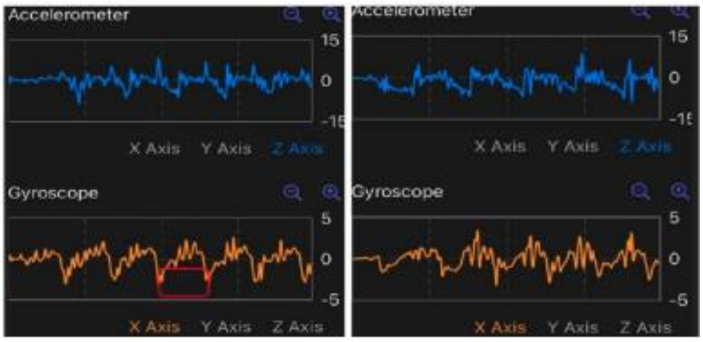

Figure 29: Results from the paretic right leg scenario of the system. The red box indicates a full gait event.

As can be observed, the gyroscope values of the healthy leg (left) provide a more consistent interval compared to the values of the paretic leg (right). The paretic leg graph values are not coherent and involve rapid changes in the angular velocity. The red outline indicates a gait cycle.

4.1.2 Assisting the impaired through handheld SLAM-based solutions

This subsection explores how the proposed solutions leverage cutting-edge technologies to create assistive environments that enhance accessibility and improve the quality of life for individuals, particularly those with disabilities. By integrating AR, SLAM, and cloud-based systems, the research demonstrates how these technologies can be used to address real-world challenges, such as improving museum accessibility and providing obstacle detection for visually impaired individuals. The results showcase practical implementations and highlight the transformative potential of these systems in creating inclusive and supportive environments.

4.1.2.1 Museum accessibility enhancement through AR cloud platforms

The minimization of user-machine interaction needs is achieved through an efficient exhibit recognition subsystem which is trained to recognize the exhibits and POIs of a museum. A combination of the two Applications, Client Application and AR Admin Application, is required for the system to work properly. First, the area needs to be scanned, using the AR implementation, and the locations of the affected exhibits must be picked. The scanning process requires a clean-of-presence area allowing for optimal feature point detection at the point of interest. When an exhibit is scanned, an anchor is placed at its location and feature-points along with related metadata are stored to the cloud. Furthermore, such Anchors are linked using a 1-

1 relationship with the affected exhibits and their multimedia assets resulting, thus, in the relation between a location and an exhibit.

The client-side application aims at improving the accessibility of impaired people while visiting exhibition sites. When the application is launched, a large distinctive button with an appropriate icon is visible at the center of the screen prompting the visitor to open the camera. Immediately the AR subsystem is initialized and the SLAM procedure recognizes the front view. Once an exhibit is visible on the device, and its feature-points are confidently identified, information about this exhibit is retrieved to the application. Due to the possibility of simultaneous recognition of nearby exhibits, the distance between the device and the affected exhibit's location is required to be less than 1.5 meters, however alternative configurations can be set in other scenarios and deployments. Figure 30 demonstrates (a) the Anchor scan and POI definition process, (b) exhibit recognition, and (c) successful exhibit information retrieval.

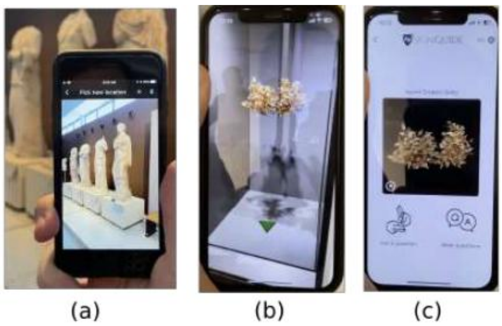

Figure 30: The AR exhibit recognition system in practice. The area is first scanned via the admin application (a) and the precise location of an exhibit is selected. Then, the area is scanned using the client application (b), the exhibit is recognized and related information is retrieved (c).

4.1.2.2 SLAM-based obstacle detection

An Android application was created implementing the aforementioned methods. From the user's perspective, the system runs on commodity Android Devices. When launched, the application requests permission for using the camera and then initializes a camera preview screen which is enhanced with AR capabilities. At the top of the screen a settings section gives the user the opportunity to display the Depth-Map and set the Low and High bounds of the threshold values. Figure 31 demonstrates the Graphical User Interface - GUI of the application described above.

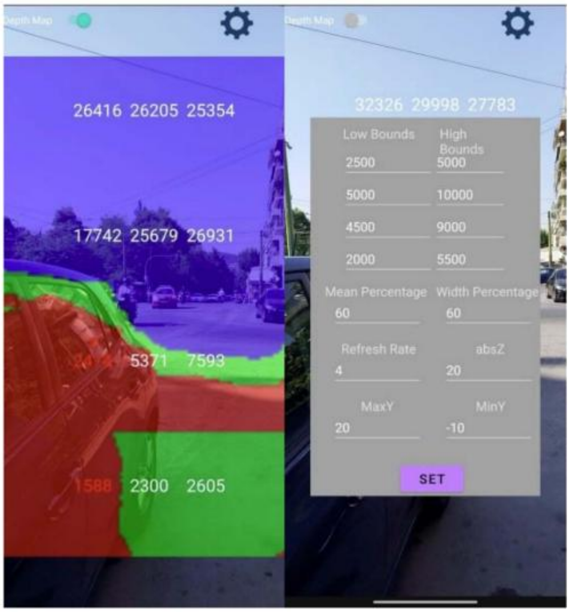

Figure 31: The GUI of the application. On the left screenshot, a grid containing distance average metrics is displayed above the depth map, since it is enabled by the switch. Blue shows large distances, green medium and red possible obstacles. On the right, the Settings page provides the ability of defining thresholds for Low Bounds, High Bounds, percentages, absolute values, refresh rate and minimum and maximum height.

4.1.2.2.1 Experimentation Setup

For the smooth operation of the application and the achievement of best results, different threshold values were entered and compared based on certain metrics. To measure the quality of each parameter, the following application state values were calculated: True Positives - TP, False Positives - FP and False Negatives - FN. True Negatives occur most of the time, reflect to the proper execution of the application and, hence, are not included in the experimentation criteria. These metrics were used for Precision, Recall and F-Score.

Precision shows which of the percentage of obstacles actually exists and Recall displays the percentage of real obstacles to the total existing obstacles. For the example values TP = 5, FP = 5, FN = 3, Precision is calculated to 50% and Recall to 62.5%, which successfully identifies the 62.5% of the real obstacles. It can be observed that increasing one metric decreases the other. To identify more objects, the accuracy of the application needs to be increased but also the FPs will be increased. A new metric is introduced to overcome this issue and achieve better balance: the F-Score which defines the harmonic mean of Precision and Recall. The F-Score is used typically for $\beta = 1$ and is called F1-Score. Therefore, F1-Score and will be used for the metrics. For the tests, the device Xiaomi Redmi Note 11 Pro 5G 3 was used in an outdoor route. The route contained: sidewalks, crossings, roads, paths and stairs and included obstacles like: trees, cars, street lights, boxes, signs, parked cars and stairs. Additionally, a broader test which included more devices and users was conducted in both indoor and outdoor environments to test the system performance and efficiency.

4.1.3 Introducing location-aware mobile intelligent systems for navigation and localization

This subsection focuses on the development and application of intelligent, location-aware systems that utilize AR, SLAM, and machine learning to provide navigation, localization, and crowd management solutions in healthcare and public environments. These systems are designed to run on commodity mobile devices, eliminating the need for infrastructure modifications while ensuring scalability and usability. The results demonstrate how these solutions can improve accessibility, optimize crowd flow, and enhance the overall user experience in complex indoor spaces such as hospitals, universities, and exhibition areas.

4.1.3.1 AR indoor navigation

The previously demonstrated technologies, concepts and algorithms have been implemented in a state-of-the-art application which is not only a proof-of-concept prototype, but an end-user product. “UNIPI: AR Experience” application is available to download for both Android and iOS9 and the innovative AR integration is in the initial release phase at the university. When opening the app, users can select their destination which lies under a 2-level categorization. The first level refers to the building where the navigation will take place and the second to the type of destination.

Currently there are two buildings supported, “Central” and “Themistokleio”, and for each building two types of routes, “Faculty” and “Classrooms” which refer to directions towards faculty offices and classrooms respectively. An additional route type called “Erasmus” is available only in “Central” building providing directions to Erasmus-related rooms. Users have to tap the Category and then the desired destination.

Starting point can either be selected via the next screen’s list, or the user is able to scan the area in front, in order for the Key Anchor system to identify his current location. After a while, arrows are displayed in the user’s screen showing the direction he has to follow, as demonstrated in Figure 32 and Figure 33. The case of a floor difference between the route’s endpoints is also covered by navigating the user to either the elevator or the stairs, and then indicate to them the next floor via on-screen dialog. While in the navigation phase, additional AR related content containing localized information may be displayed on the user’s AR screen.

[9] https://unipi-ar-experience.web.app/

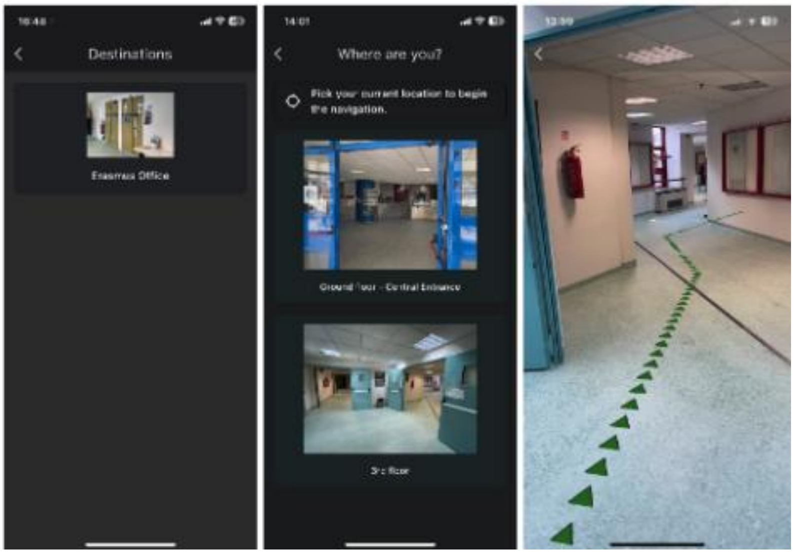

Figure 32: The AR Navigation system in practice. The user selects the destination (left), picks the current location (middle) and the navigation begins (right).

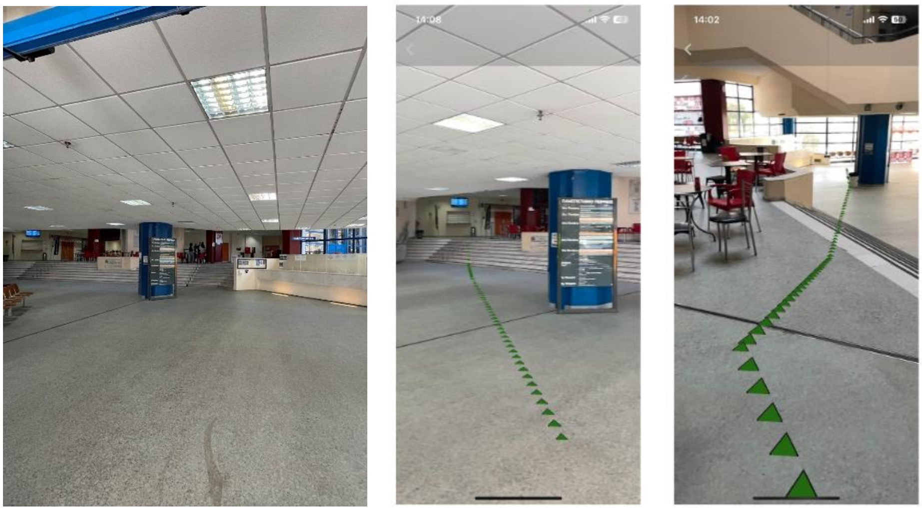

Figure 33: Snapshots of the system showing directions in various locations of the experimentation site, comparing the original area (left) and the navigation arrows (middle, right).

4.1.3.2 ML-enhanced AR localization

The ML-enhanced AR localization ideas, and algorithms have been put into practice in a cutting-edge application that serves as both an end-user product and a proof-of-concept prototype.

The Administrator App handles the initial Route creation process along with the management of the system data. A Route is a sequence of AR Cloud Anchors and, hence, the Route creation process consists of opening the camera feed, positioning the Anchors at the respective locations and uploading the Anchor data to the Cloud. This process is performed by pressing the "Plus" button of the Admin app. Additional Route information, including the final destination name, the room or floor and an image thumbnail, is defined. Finally, the administrator is able to edit the Route information or perform a new area scan by pressing the "Edit" button or delete the Route via the "Delete" button. The new area scan can either replace the initial Feature Map of an Anchor or be used concurrently during the resolve process.

The User App allows the visitors to select the final destination and begin the navigation. When opening the app, the visitor is prompted with a list of the available destinations (e.g. a professor office). Once a destination is selected, a screen containing a camera preview is rendered while the AR Cloud Anchor resolve procedure begins in the background. If an Anchor is resolved, the corresponding 3D model is visualized at the defined location. When the Anchor of the next Route way point is also resolved, a sequence of guidance Anchors is programmatically attached, resulting in displaying a visualized path. At the same time, for every successful resolve, the system is retrained by initiating the procedure of re-uploading that Anchor, using the Feature Map generated from the current state of the area. The distance from the last Anchor of the Route is continuously monitored and when it reaches a predefined threshold (2 ms), a message for reaching the destination is displayed to the visitor. Snapshots of the system in practice are shown in Figure 34

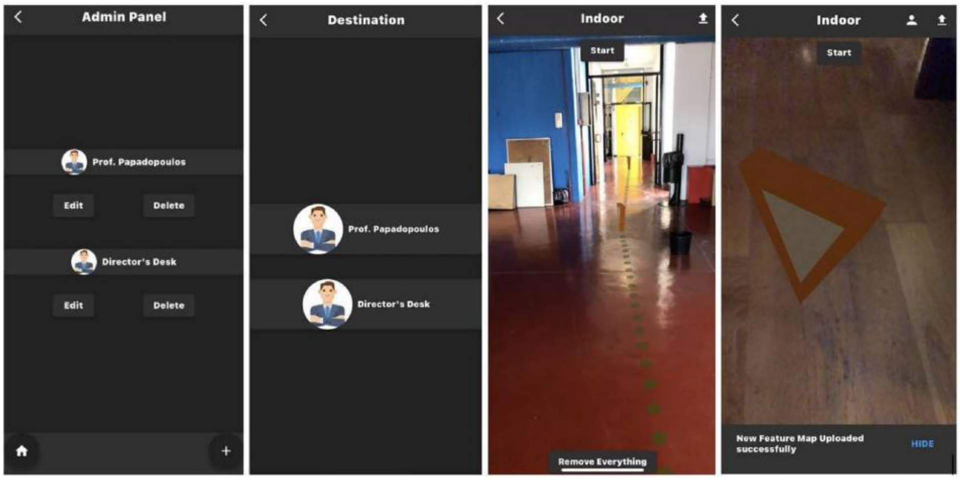

Figure 34: The ML-enhanced AR localization system in practice. The admin (far left) edits the destinations to be selected by the user (left). Navigation arrows are presented (right) and the system is retrained upon visiting an already resolved arrow (far right).

4.1.3.3 AR gamified crowd management

The prototype system has been tested in a real user scenario at Hellenic Model Railways Club - HMRC exhibition site, a model train club in Athens, Greece, which contains three exhibition sections. Client and Administrator applications were developed, which exchange data with the serverless functions, database and storage of the Cloud infrastructure.

HMRC Client Application

The HMRC Client Application utilizes AR and gamification in two scenarios: 1. to guide the user through the exhibits and prompt them to gain exhibit information by inserting intriguing AR content and 2. to monitor the next section's crowd status and prompt the user to play an AR game, which includes content referred to the current section, with the goal of delaying the user before entering the next section. The guide through the exhibits includes AR information marks which pop up exhibit related content once tapped. The presented content is also related to the next section crowd, displaying larger texts with more information (or maybe a video) if the user needs to be further delayed, acting as a first stage of crowd management. When the user reaches the end of this section's AR guide, the next section's crowd status is again checked, and if it is determined that it is crowded, the user is prompted to take part in AR games.

HMRC AR Administrator

The HMRC AR Administrator application is responsible for authenticating the users and defining and modifying sections along with their respective data. Section data can either be the max visitors or current visitors state, content for the AR exhibits inside this section and content for the AR games. Moreover, this application handles the Anchor creation, upload and modification procedures. The user opens the AR screen, scans the frontal scene and selects a location for the Anchor to be attached before proceeding with uploading the Anchor to the Cloud.

4.1.3.3.1 Game scenarios

There are two AR game scenarios that are designed for this proof-of-concept prototype to highlight the feasibility of developing such systems: AR Catch-TheAns and Tre(AR)sure Hunt. AR Catch-The-Ans is a classic knowledge game, in which AR content is displayed in front of the visitor and it is asked to select the correct object following the form of AR multiple choice. The content of this game is correlated with the sections exhibits and checks whether the user has understood the exhibits that he has visited. Moreover, a score is generated and compared to others in the form of leaderboards, acting as a motivating factor for the user to play the game again in order to gain a higher score. In the Tre(AR)sure Hunt game, Anchors are attached at hidden locations in the section and once the visitor identifies them, additional information is presented. These two games are played in this sequence, and aim at delaying the user in a more comprehensive and pleasant way rather than just notifying him about a possible waiting time. Snapshots of the in-game environment are presented on Figure 35.

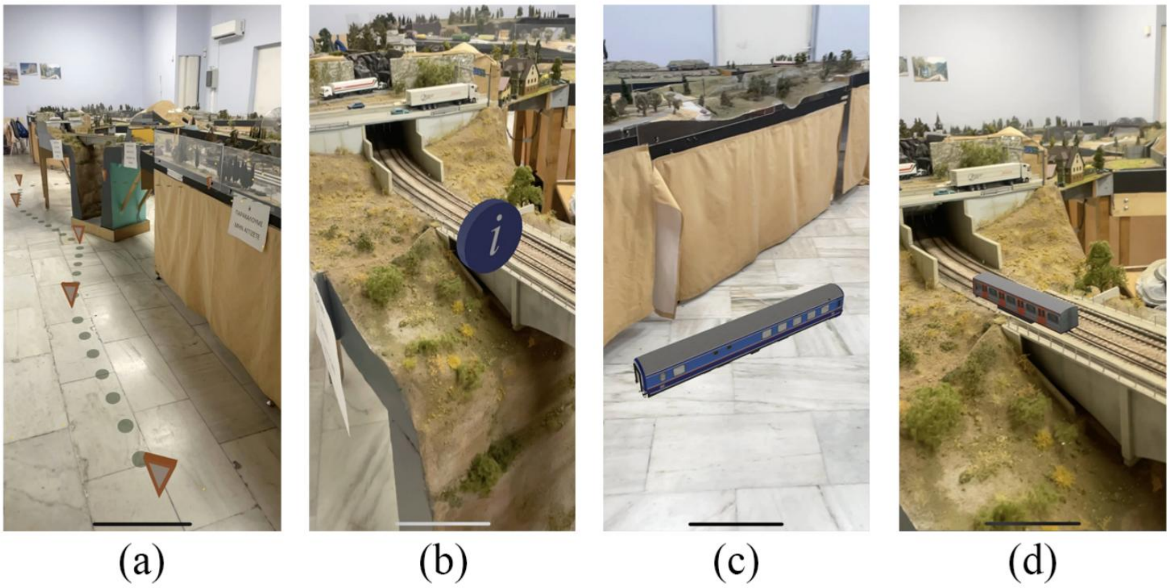

Figure 35: Game scenarios of the AR gamified crowd management system. The navigation arrows showcasing the exhibition route (a) and augmented information about the exhibition (b) are always visible in each exhibition section. Additionally, snapshots from the AR Catch-theAns (c) and TreARsureHunt (d) games are presented.

4.1.4 Facilitating medical education through AR and CV

This subsection highlights how the integration of AR and computer vision (CV) technologies can revolutionize medical education and training. By creating interactive and immersive learning environments, the proposed solutions empower healthcare professionals and students with tools to better understand medical concepts, such as drug properties and molecular structures. The results showcase the practicality and educational value of these systems, emphasizing their ability to deliver engaging and impactful learning experiences using commodity mobile devices.

4.1.4.1 Mobile drug compound education platform

The end user solution is offered as an Android or iOS application and both executables have been developed and tested under real conditions. For the purpose of this thesis, all demonstrations and screenshots are captured on an iOS device, as shown in Figure 36. The user selects the “Start capture” button and is diverted to the main screen of the app. Camera preview along with augmented 3D models for any identified medicine are rendered on the screen. Tapping at a compound will navigate to the details screen.

Paracetamol was used as a demonstrative example. This tested pharmaceutical product contains disks of 500g of Paracetamol with the title of the drug being Acetaminophen. The record of Acetaminophen/Paracetamol is retrieved from the PubChem database along with the appropriate 3D model of the molecules.

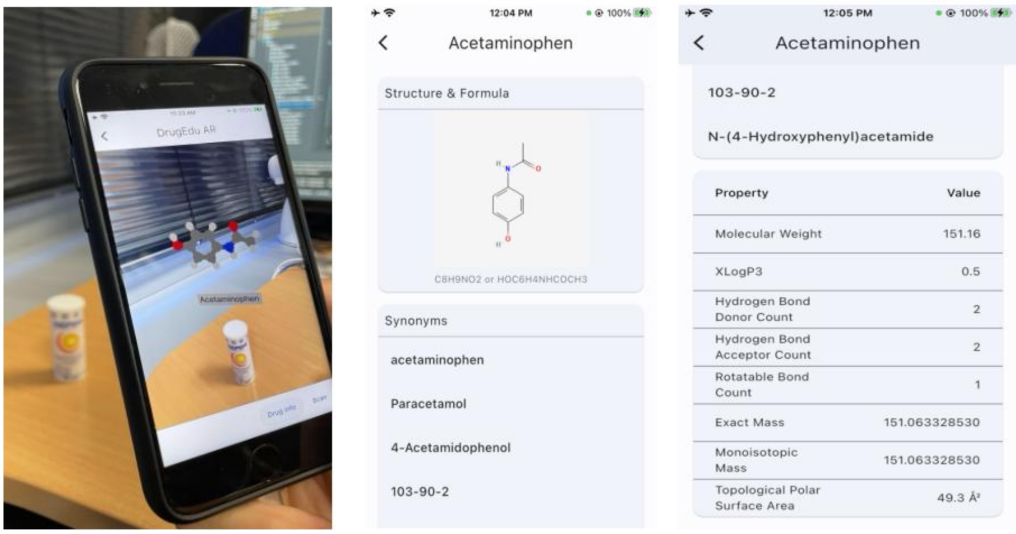

Figure 36: Snapshots from the AR Drug Identifier prototype system in practice. Once the system identifies a drug box it displays its molecular compound above (left). Upon selecting the compound, clearer visual information about the compound is displayed (middle) along with all the retrieved properties (right).

4.2 Evaluation

This section outlines the evaluation of the proposed systems, providing insights into their effectiveness, performance, and impact within healthcare contexts. For most of the studies, both quantitative and qualitative benchmarks are provided.

4.2.1 Engaging users for increasing their physical and mental activity and RPM using AR, IoT and IMU technologies

This subsection assesses the effectiveness of the proposed AR, IoT, and IMU sensor-based solutions in promoting physical and mental activity while enabling real-time health monitoring.

4.2.1.1 Gamified AR and IoT platforms for remotely assessing physical activity

Focusing on the evaluation of the gamified AR and IoT platform, this subsection examines its performance, usability, and impact on user engagement and physical activity through quantitative and qualitative metrics.

4.2.1.1.1 Quantitative Evaluation

The developed AR exergame prototype has the advantage of not requiring any extra hardware. Therefore, the prototype was tested 10 times for each question type on four devices: Galaxy A20, Galaxy A7 2018, TCL 20 5G and Huawei P20 Lite.

Results show average performance metrics of 10 sessions for each type. Each session contains 10 quests. The battery drain is calculated by the difference of the battery percentage between the start and the finish of each session. The FPS are counted from the first to the last test. Table

1 shows the average performance metrics from 10 tests of text type questions for each device. Table 2,Table 3 Table 4 show the same metrics from object, box, and sort challenges accordingly.

Table 1: Average results of 10 tests of 10 text question sessions

Device	**Battery Drain**	**FPS (min/avg/max)**
Galaxy A20	0.9%	17/33/60
Galaxy A7 2018	1.1%	16/32/59
TCL 20 5G	0.6%	16/31/61
Huawei P20 Lite	1.8%	13/29/57

Table 2: Average results of 10 tests of 10 object question sessions:

Device	**Battery Drain**	**FPS (min/avg/max)**
Galaxy A20	1.1%	11/29/58
Galaxy A7 2018	1.3%	13/31/59
TCL 20 5G	0.9%	14/30/60
Huawei P20 Lite	2.8%	12/27/58

Table 3: Average results of 10 tests of 10 box question sessions

Device	**Battery Drain**	**FPS (min/avg/max)**
Galaxy A20	0.9%	20/36/59
Galaxy A7 2018	1.1%	23/37/59
TCL 20 5G	0.7%	21/39/60
Huawei P20 Lite	2.3%	18/31/59

Table 4: Average results of 10 tests of 10 sort quest sessions

Device	Battery Drain	FPS (min/avg/max)
Galaxy A20	1.0%	16/31/59
Galaxy A7 2018	1.4%	19/30/57
TCL 20 5G	1.1%	23/34/59
Huawei P20 Lite	1.9%	14/28/58

4.2.1.1.2 Gamification Analysis

Apart from the performance analysis, evaluation of the core gamification aspects was also performed. More specifically, the game was tested on 18 users aged 20–40 and 15 users aged 40–60. Each session contains 10 questions; the parameters of steps, session duration (in minutes), heart rate, and hand trembling were recorded. For the steps and heart rate measurements, a smartwatch device was used. Trembling was calculated using the device's accelerometer and classified on levels from 1 to 4. The following tables show the results of 10 sessions for each question type. Table 5 shows the average medical metrics of users aged 20–40 and Table 6 the same metrics from users aged 40–60.

Table 5: Average results for users aged 20–40

Question Type	Steps	Duration	Heart rate	Trembling
Text	533	4.9	71/86/121	1
Object	581	5.8	82/101/123	2
Box	499	5.3	80/111/129	1
Sort	551	5.7	73/102/128	1

Table 6: Average results for users aged 40–60

Question Type	Steps	Duration	Heart rate	Trembling
Text	600	6.9	65/83/116	2
Object	591	6.8	61/86/111	3
Box	523	6.2	68/88/112	2
Sort	588	6.9	62/86/110	3

Results show that the users are physically active while playing the game, keeping a good pace and with average heart rate. Comparing age groups, results show that the average game duration, steps, and trembling of the 40–60 group age were slightly larger than the metrics of the other group, while heart rate averages followed the opposite direction.

4.2.1.1.3 Qualitative Evaluation

The main objective of this work was the development of the AR gamification platform and the proof of concept for combining the AR and IoT technologies in the health domain. Therefore, the evaluation of the system focused on the analysis of the overall architecture and the assessment of its usability. For the evaluation of the usability of the system, a technology acceptance questionnaire was produced and circulated to the previously presented user groups. The questionnaire included a list of questions in order to assess the perceived usefulness, the perceived ease of use, and the intention to use, each one of which could be answered with one of the following responses:

- Totally disagree (−3);
- Disagree (−2);
- Slightly disagree (−1);
- Neither agree not disagree (0);

- Slightly agree (+1);
- Agree (+2);
- Totally agree (+3).

Technology Acceptance Question	Average Result
I think the AR game is a good idea.	2.3
I believe it is easy to use the AR game mobile app.	1.9
I believe it is easy to use the AR game wearable app.	2.0
I think the AR game is a user friendly technology to interact with.	2.1
I did not have any problems using the AR game in my room.	1.3
The use of the AR game will have a positive impact to my health.	1.6
The use of the AR game could help me to become more active.	1.8
I have the intention to use the AR game daily.	1.9

Figure 37: Technology Acceptance questionnaire responses and average results.

The results shown in Figure 37 indicate very positive feedback from the users on the AR game system and very good perceptions on the impact that the use of the system had on their health. Some usability aspects could be improved as well as the ability to use the system in smaller rooms and more complex environments.

4.2.1.2 Cloud-Enabled Gamification to Enhance Participation in Nature-Based Solutions

Performance metrics were captured in order to provide a clear view of how the system interacts with the users in the context of human-machine interaction principles. Tests were performed for various devices concerning loading times, FPS, MB consumed, and battery drain as metric parameters. All devices were tested for a duration of 5 minutes and were set to display 12 anchors each. Each test was repeated for 10 times, resulting in a total of 30 tests. Results of the experiment are presented in Figure 38. The three hardware ranges of phones that were tested demonstrated a pleasant execution of the prototype application. Although FPS metrics may vary, everything above 30 FPS is considered totally acceptable concerning a user experience in a mobile device.

Device	OS	Loading Time	FPS	Data Usage	Battery Usage
iPhone SE 2020	iOS 15.5	3.1s	48	8.5MB	1.2%
iPhone 12	iOS 15.6	2.9s	53	9.1MB	0.8%
Huawei ANE LX1	Android 9	4.2s	36	7.6MB	1.3%

Figure 38: Performance metrics of the NBS AR Gamification system for three different commodity mobile devices.

4.2.1.3 Remote gait asymmetry detection

The recorded data is evaluated based on the precision of gait cycle identification. Therefore, a set of metrics in the form of ground truth is required to compare to the recorded IMU sensor values. In the proposed system, the need was to compare the gait cycle durations to valid proof of the same durations. Hence, video recordings were utilized which captured the whole measurement procedure at 60FPS, 1080p. The videos were later annotated to define the gait event interval timestamps via observation. These timestamps were compared with the application data to try and find a possible error margin. Table 7 and Table 8 demonstrate comparative results of Heel Strike event timestamps from the healthy left leg for five consecutive gait cycles of two separate tests.

Table 7: Comparison between the applications and the video recording measurements of the first test.

Gait Event	Phone Gyroscope	Video Recording
1	612 ms	590 ms
2	1105 ms	1080 ms
3	1816 ms	1790 ms
4	2389 ms	2420 ms
5	2958 ms	3050 ms

Table 8: Comparison between the applications and the video recording measurements of the second test.

Gait Event	Phone Gyroscope	Video Recording
1	727 ms	740 ms
2	1298 ms	1220 ms
3	1976 ms	2010 ms
4	2549 ms	2530 ms
5	3011 ms	2990 ms

4.2.2 Assisting the impaired through handheld SLAM-based solutions

This subsection evaluates the effectiveness of the proposed SLAM-based solutions in enhancing accessibility for impaired individuals, including museum exhibit recognition and obstacle detection systems.

4.2.2.1 Museum accessibility enhancement through AR cloud platforms

The proposed system has been tested at the exhibition of AMT under real usage scenarios with visitors present. Eight museum exhibits have been selected for the test using four different mobile devices: iPhone 12, iPhone SE 2, Galaxy A52s and Galaxy Tab S8 Ultra. Ten tests were performed for each device, for each exhibit, examining the recognition process. Five of the tests searched for the exhibit in its frontal space while five started the procedure at a 45° angle. Table 9 demonstrates average results from 5 tests conducted on each exhibit, with a total of 40 tests, highlighting the time required for each device to successfully detect the exhibit along with a success rate, when searched from the frontal space.

Table 9: This table demonstrates time and success rate from exhibits scanned using the client app from the frontal space, without an angle.

Device	Time(s)	Test success rate (out of 5)
iPhone 12	3.39	96% (4.80)
iPhone SE 2020	4.11	94% (4.70)
Samsung Galaxy A52s	4.43	93% (4.66)
Samsung Galaxy Tab S8 Ultra	4.01	95% (4.74)

Table 10 demonstrates the same number of tests, but exhibits were scanned from a 45° angle.

Table 10: This table demonstrates average time and success rate from exhibits scanned using the client app from an angle of 45°.

Device	Time(s)	Test success rate (out of 5)
iPhone 12	3.56	95.2% (4.76)
iPhone SE 2020	4.33	93.6% (4.68)
Samsung Galaxy A52s	5.01	94% (4.70)
Samsung Galaxy Tab S8 Ultra	4.21	94.4% (4.72)

Results from the tests show that although there is a slight decrease in recognition duration and success rate when scanned from an angle, overall performance of the system is well accepted, considering that there is no reference point (e.g. QR Code) or other identification intervention.

4.2.2.2 SLAM-based obstacle detection

4.2.2.2.1 Performance

Performance tests were conducted to assess the application’s executability. The Screen Refresh Rate was calculated as a metric of measuring the load and, hence, the efficiency of the execution of the algorithm. Since the camera feed is not refreshing with the same rate that the algorithm is executing, the number of dropped frames was recorded along with the total number of frames that theoretically should have been rendered, computing the following ratio:

$$Dropped\% = (\ Dropped\ Frames\ /\ Theoretical\ Frames\ ) \times 100\%$$

Larger values show lower performance.

Different algorithm execution intervals were tested capturing Dropped%, Energy, FP and FN. The Refresh Rate of the camera feed was set to 30 Frames Per Second - FPS (the ARCore maximum) and percentage of the dropped frames was calculated based on the total executions of the algorithm. Battery drain percentage was measured. Tests included the executions of the algorithm for f = 2, 3, 4 and 5 times per second. 13 10-minute tests produced average results that are demonstrated in Figure 39.

For f = 2, algorithm failed to locate 2 obstacles while others successfully identified all obstacles. The value f = 4 shows the best results, although a relatively large percentage of drop in frames.

Overall, the system was fine-tuned and tested under real usage scenarios. Having the algorithm executed at the optimized value (f = 4), the system was broadly tested in a larger set of devices and in different scenarios. Specifically three different devices were choose, representing low-end, mid-range and high-end device categories:

- Samsung Galaxy A20 (low-end)
- Motorola Edge 30 Neo (mid-range)

- Google Pixel 6 Pro (high-end).

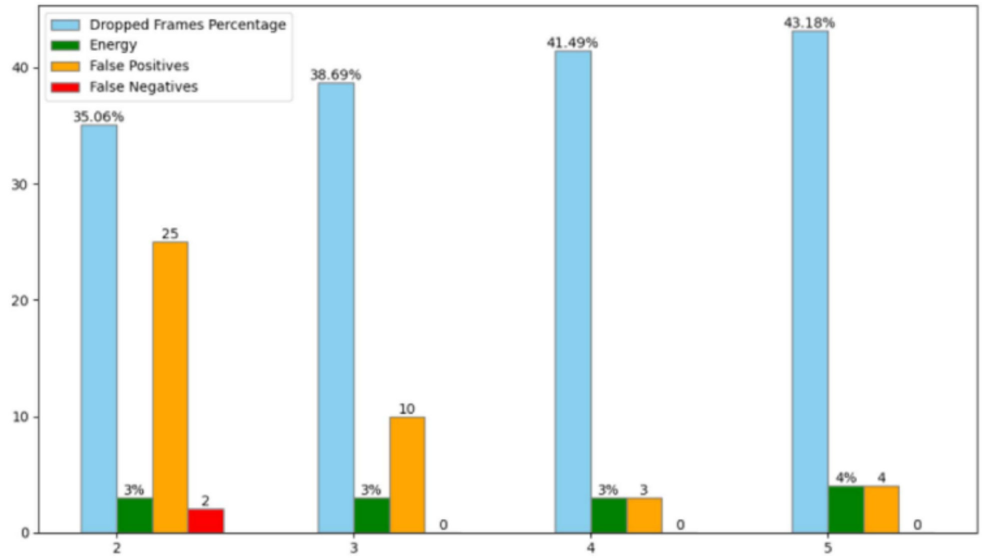

Figure 39: Dropped Frames % and Energy, FP and FN while executing the algorithm 2, 3, 4 and 5 times per second for 13 10-minute tests

For the tests, 3 users (one for each device) performed 10 obstacle detection tests for each device, in two locations, one indoor and one outdoor. The indoor route was tested with lights turned on and off, having a total of 90 tests. For each device, average values of: Battery drain, Frames Per Second - FPS, FPs and FNs were captured.

Table 11, Table 12 and Table 13 demonstrate the results of the tests on the indoor with lights on (30 tests), indoor with lights off (30 tests) and outdoor (30 tests) route accordingly. The indoor area includes 6 obstacles while the outdoor 15. Figure 40 demonstrates the execution of the application in indoor environment with lights on and off.

Table 11: Average Results of 30 Tests Performed at an Indoor Environment with a Total of 6 Predefined Obstacles and the Lights Turned On. The performance curve is following the device specifications curve.

Device	Battery Drain %	FPS	FP	FN
Samsung Galaxy A20	2%	14.01	1	2
Motorola Edge 30 Neo	2%	22.36	1	0

Google Pixel 6 Pro	1%	29.87	0	0

Table 12: Average Results of 30 Tests Performed at an Indoor Environment with a Total of 6 Predefined Obstacles and the Lights Turned Off. The performance curve is following the device specifications curve and is lower, due to the higher processing power required to run the SLAM algorithms in lower lighting conditions.

Device	Battery Drain %	FPS	FP	FN
Samsung Galaxy A20	4%	12.99	2	2
Motorola Edge 30 Neo	3%	20.82	1	1
Google Pixel 6 Pro	2%	24.10	0	0

Table 13: Average Results of 30 Tests Performed at an Outdoor Environment with a Total of 15 Predefined Obstacles. The performance curve is following the device specifications curve.

Device	Battery Drain %	FPS	FP	FN
Samsung Galaxy A20	3%	18.24	2	3
Motorola Edge 30 Neo	2%	24.17	1	2
Google Pixel 6 Pro	1%	29.15	0	0

Figure 40: Execution of the system in indoor area. On the left, the obstacle is identified successfully with lights on (distances highlighted with red), while on the right, the stairs are identified successfully, with lights off (distances highlighted with blue).

The correct values identify obstacles and cliffs efficiently, while performance and energy consumption is maintained at an acceptable level. Even in lower-end devices, like the Galaxy A20, although the FPS are in low levels, the system is still performing and notifying the user for upcoming obstacles or cliffs, which is the purpose of this section of the thesis.

4.2.2.2.2 Qualitative

A qualitative evaluation was also performed to assess the usability of such systems from the non-technologist user perspective. The evaluation was done in the form of interviews, with questions being based on the following pillars: Usability (ease of use and accessibility), Learnability (how easily the system is understood), Performance (did the system help with obstacle avoidance), Satisfaction and trust and, finally, Limitations. Five individuals aged from 21 to 65, owning Android phones and with zero to no expertise in technology, were asked questions based on these pillars, after informed consent was obtained. Results from the interview highlight that although the users do not know exactly how the system is implemented, the voice and tactile feedback along with the ability to use the application in their own device and the efficient obstacle detection, this system increases accessibility and willing of use. Concerning the learnability, the system requires no user setup and can be used instantly resulting, thus, in positive user feedback. Overall, the users were satisfied, and the system exudes confidence to use it while the only comments and drawbacks are the currently limited availability to only Android devices, the overall use of a mobile device, if the user is visually impaired and the requirement to hold the device at the correct position.

4.2.2.2.3 Comparison

A complete comparison between the thesis work and other approaches is shown in Table 14. Although other approaches which utilize ML or hardware can achieve obstacle detection, they are not fulfilling the aspects that the thesis system fulfills.

Table 14: Comparison of the thesis work to other approaches

Approach	Commodity Device	Offline	No Cost	Hardware Independence	Lightweight
RFID		X			
Camera		X			
Wearable		X			X
LiDAR		X	X	X	X
ML on device	X	X	X	X	

Other SLAM	X	X	X	X	
Cloud ML	X		X	X	X
Current	X	X	X	X	X

4.2.3 Introducing location-aware mobile intelligent systems for navigation and localization

This subsection evaluates the proposed location-aware mobile intelligent systems, focusing on AR-based indoor navigation, ML-enhanced AR localization, and gamified crowd management, highlighting their performance, adaptability, and impact on user accessibility and experience in complex environments.

4.2.3.1 AR indoor navigation

The most important aspect for evaluating an AR indoor navigation application is the time required for a commodity device to first localize itself and then correctly display the desired checkpoints at their precise locations. The thesis concludes that two metrics are important and attempted to be optimized: duration of first Anchor identification and Anchor displacement error.

Two Anchor hosting methods were used:

- **Method 1**: hosting each Anchor in an individual AR session and
- **Method 2**: hosting all Anchors in the same session.

For each test the results were compared to the Anchor hosting method that was used, using two devices: an iPhone SE 2020 and a Huawei H20 Pro. Table 15 demonstrates results of the metrics and is clearly indicated why Method 2 was finally selected for the route recording process. In a single AR session, the surrounding feature points are more than one time visited and are more precisely recorded, thus resulting in better SLAM.

Table 15: Comparison table between individual and same hosting sessions highlighting the displacement and duration differences.

Device	Duration(s)	Displacement(cm)	Hosting session
iPhone SE 2020	4.32	22.6	Individual
Huawei H20 Pro	6.01	30.1	Individual
iPhone SE 2020	2.99	12.4	Same
Huawei H20 Pro	4.24	21.9	Same

Table 16 indicates the number of successful tests compared to their missing Anchors. 58% of the tests had no missing Anchors while tests with one, two or even three Anchors still showed a successful navigation, resulting in the final 85% of successful navigations. Routing algorithm is developed in such a way that if a checkpoint is not recognized, but the next one is, navigation will proceed to the next checkpoint overcoming the current.

Table 16: Table showing metrics of a total of 100 tests. Metrics include the percentage of navigations with zero to 4+ missed anchors and the destination reach success rate.

Anchors missed	Tests performed	Destination reached
0	58	100% (58)
1	24	83.3% (20)
2	8	25% (6)
3	6	50% (1)
4+	4	0% (0)

4.2.3.2 ML-enhanced AR localization

Upon completing development, tests were conducted including the proposed CML approach along with performance and resource measurements. The thesis uses the Resolve Duration—RD as a criterion for measuring the effectiveness of the algorithm. As RD the thesis defines the duration between the initial request for resolving a Cloud Anchor and the moment that the Anchor is placed. Several experiments were conducted using an iPhone X iOS device running iOS 16. For a particular room, a Route was recorded and navigated through it using the CML enabled application. For each navigation, RD of the Anchors which belong to a single Route Checkpoint was recorded, which are defined as Anchors per Checkpoint—APC.

Initially, there was only one APC, the one recorded from the Administrator application. After some Route iterations, more Anchors are attached to each Checkpoint. Afterwards, the room underwent various modifications (e.g. removal of small objects like a chair) and the navigation was restarted. The RD of the Checkpoints was recorded in correspondence to the number of APC. Figure 42 and Figure 43 demonstrate the average RD of the first Anchor of a route, for unmodified and modified room states during 40 route iterations for each state. The first line of each table refers to the initial recording (with one APC) of the route and acts as a comparison point between already developed AR navigation systems and the injection of the proposed algorithm. Results show that when there are no changes in the room environment, the initial recording resolves the Anchors significantly faster compared to the modified room state, which also confirms the assertion of the problem that the thesis aims to solve. For both states there is a decrease in the resolve duration as the number of APC is increased until it reaches a number above which the resolve duration is leveled. Hence, the navigation is not improved much since the newly generated Feature Maps are more similar to the ones recorded. Key observation of the tables is that although the modified room state requires almost double the time using only the initial recording, the RD tends to coincide to a large extent as the CML algorithm is generating more Anchors. Up to 10 APC there is a continuous and calculable time reduction, while thereafter not much. This is also illustrated in Figure 41 where the green and blue lines show the modified and unmodified room state RD as the number of APC increases.

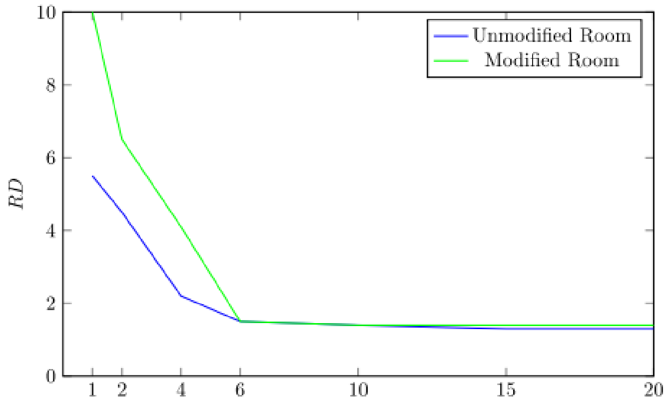

Figure 41: Figure showcasing the initial Resolve Durations (RD) for different Anchors Per Checkpoint (APC). The RD is not decreased much after 6 APC, resulting thus in the conclusion that more than 6 APCs are redundant.

APC	Initial Anchor RD	Battery	Network
1	5.5 s	0.4%	0.75 MB
2	4.5 s	0.4%	1.5 MB
4	2.2 s	0.6%	3 MB
6	1.5 s	0.8%	4.5 MB
10	1.4 s	0.8%	7.5 MB
15	1.3 s	1.1%	11.25 MB
20	1.3 s	1.3%	15 MB

Figure 42: Metrics of Anchors Per Checkpoint (APC), initial Anchor Resolve Duration (RD), battery drain and network usage. As the APCs increase, RD decreases and the other metrics increase.

APC	Initial Anchor RD	Battery	Network
1	10 s	0.7%	0.75 MB
2	6.5 s	0.6%	1.5 MB
4	4.1 s	0.5%	3 MB
6	1.5 s	0.8%	4.5 MB
10	1.4 s	0.8%	7.5 MB
15	1.4 s	1.1%	11.25 MB
20	1.4 s	1.4%	15 MB

Figure 43: Metrics of Anchors Per Checkpoint (APC), initial Anchor Resolve Duration (RD), battery drain and network usage, in rooms with modifications compared to the initial training. As the APCs increase, RD decreases and the other metrics increase. The initial RD is observed to be high, due to the modifications, but the following are significantly lower, justifying that the proposed algorithm is working.

Apart from the algorithmic scope of this work, the proof-of-concept prototype needs to be also tested for being able to run such algorithms without consuming the resources of the device or the network. Hence, battery drainage and network traffic were recorded, as demonstrated in Figure 42 and Figure 43. The last two columns show the average battery drain and network usage per route of 3 Checkpoints, for 40 routes of unmodified and modified room states accordingly. Results show that there is no significant increase in battery usage for different numbers of APC and so it is concluded that the hardware is feasible to support such an implementation, at these levels of complexity. Concerning the network traffic, it is normal to see an increase in the kilobytes, but the overall usage of around 0,75MB per Anchor is considered minor in the 5G era. The data usage in the optimal scenario of 6 APC (above which the RD is not decreased significantly) is increased by almost 7MB per route session, which is an accepted value compared to the 5.5 s (unmodified) and 10 s (modified) to 1.5 s decrease in the RD. Other limitations regarding the AR recording speed, device orientation, lighting conditions and best device movement practices are assumed to been taken into account.

4.2.3.3 AR gamified crowd management

The AR gamified crowd management system developed for this thesis is focused on the applicability of such systems and presents the development process of a functional cloud system for a real user scenario. Metrics regarding the AR creation and recognition process are recorded along with data from visitor tests. A simulation of a large-scale scenario was conducted by populating the database with fictional crowd data for the next sections to check whether the two crowd management methods are triggered. The system was tested in both Android and iOS for game performance and Cloud AR functionality. For both metrics battery drainage along with content loading time were measured. For the game performance, the system was tested between three different model LOD variants (1: 1000 to 2000 triangles, 2: 500 to 1000 triangles, 3: up to 500 triangles).

Table 17 shows results of the three LOD levels that were tested. The thesis concludes that LOD 1 is only playable at higher end devices, such as iPhone 12 while lower LODs can be played in older devices too. Playable games are considered with average metrics above 30 FPS.

Table 17: Results of 5 tests of each LOD variant for each device for 2 min. LOD 1 is only playable at higher end devices, such as iPhone 12 while lower LODs can be played in older devices too. Playable games are considered with average metrics above 30 FPS

Device	Loading	FPS	Drain	LOD
iPhone 12	1121ms	38.1	0.8%	1
Huawei H20 Pro	4235ms	18.4	1.6%	1
iPhone SE 2020	2179ms	32.6	1.9%	1
iPhone 12	891ms	50.9	0.7%	2
Huawei H20 Pro	3150ms	27.1	1.4%	2
iPhone SE 2020	1539ms	39	1.7%	2
iPhone 12	612ms	55.8	0.7%	3
Huawei H20 Pro	2051ms	39.3	1.2%	3
iPhone SE 2020	1299ms	47.4	1.7%	3

4.2.3.3.1 Qualitative Evaluation

Concerning the usability of such system, although the site was not crowded, museum visitors of the day of the tests were able to watch the game being recorded and played. Some of them even tried to play some portions of the game, with a total of 9 people involved in the process, one of whom was president of the Club. Visitors and club members had the change to answer a brief Technology Acceptance Questionnaire for assessing Perceived Usefulness, Perceived Ease of Use and Intention to Use. Answers are ranged from Totally disagree (-3) to Totally Agree (3) with Disagree (-2), Slightly disagree (-1), Neutral (0), Slightly agree (1) and Agree (2) between them. Results are demonstrated as follows:

- I think the AR game is a good idea: 2.83
- It is easy to use and interact with the app: 2
- I think the AR game was educative: 2.16
- The use of the AR game entertained me while waiting: 1,88
- I would like to use it in other museums: 1,66

4.2.4 Facilitating medical education through AR and CV

This subsection evaluates the integration of AR and Computer Vision technologies for medical education, focusing on the effectiveness of the proposed drug identification platform in enhancing learning experiences and knowledge retention for healthcare professionals and students.

4.2.4.1 Pharmaceutical substances education

The utilization of AR and Text Recognition offers pragmatic data visualization and comprehensive information transmission. One of the benefits that defines the proposed solution is the ability to perform multiple drug recognitions at once. Many medicine boxes can be laid in a table and users will be able to view their molecular compounds and information just by hovering their phone above. Another aspect of this part of the thesis is the interoperability and ease of access. The cross-platform design architecture allows the application to run on any OS thus increasing the field of application and use. Furthermore, data structures and architecture models are designed in such a way that not only are able to connect to the PubChem database but offer a generic interface that is able to interop with any related data storage. The general approach is to offer an intelligent environment that expedites the learning of visualized medical information by exploiting computer vision technologies: AR and Text Recognition.

5 Discussion

This section discusses the outcomes of the conducted research, highlighting its main contributions, reflecting on the lessons learned, examining encountered challenges and methods to overcome them, and situating the work within a broader application context. Finally, it outlines potential directions for future research.

5.1 Contributions

This subsection summarizes the key contributions of the research, emphasizing the novel aspects introduced and their significance to the field. Each contribution of this dissertation is presented in accordance with the research question it addresses, as defined in the Introduction section.

5.1.1 Question 1: Can commodity mobile devices facilitate efficient assistive living?

Commodity mobile devices can facilitate efficient assistive living. Extensive insights from the thesis demonstrate that such devices, leveraging their built-in hardware, support various healthcare applications. The thesis highlights several examples where commodity devices, such as smartphones, are utilized effectively. AR-based solutions, for instance, enable the creation of immersive environments that combine physical and digital elements to motivate users, increase physical activity, and monitor health metrics. AR navigation principles, supported by cloud-based SLAM architectures, allow for seamless indoor guidance, enhancing user accessibility without the need for costly hardware installations. Additionally, these devices can detect gait asymmetry in stroke rehabilitation by using their built-in IMU sensors, offering an affordable and accurate method for assessing movement at home. The utilization of IoT devices further extends the capabilities of these mobile platforms, enabling real-time monitoring of bio-signals such as heart rate, steps, and hand tremors. These findings underscore the versatility of commodity devices in creating cost-effective, user-friendly, and scalable assistive living solutions. Examples of how the research addresses this question include:

1. **AR Exergames for Physical and Mental Activity**: The research developed AR-based exergames that run on commodity smartphones, allowing users to increase their physical activity and mental engagement while being monitored by healthcare professionals. For instance, users could interact with AR elements in their living spaces during gamified scenarios, such as catching virtual objects, while their biometrics (e.g., heart rate and steps) were tracked via IoT wearables. This application highlights how commodity devices can transform a simple home environment into an engaging and interactive healthcare space.

2. **Gait Asymmetry Detection Using IMU Sensors**: A novel system was introduced to detect gait asymmetry in patients undergoing rehabilitation. By utilizing the accelerometer and gyroscope sensors of smartphones, the system identified gait cycles and asymmetries without requiring specialized wearable devices or laboratory setups. This solution empowers patients to monitor their progress at home, reducing the need for frequent hospital visits and enabling remote interventions by healthcare professionals.

3. **SLAM-Based Obstacle Detection for Visually Impaired Individuals**: The research implemented a mobile application that uses SLAM and depth estimation to detect obstacles and downhill cliffs, providing real-time feedback through haptic and audio cues. This system showcased how commodity devices could serve as assistive tools for

visually impaired individuals, eliminating the need for expensive external hardware while improving accessibility.

4. **AR in NBS for Outdoor Engagement**: By combining AR, IoT, and gamification, the research extended the benefits of commodity devices to outdoor environments. In the NBS application, users were motivated to visit urban green spaces through AR-based badges, leaderboards, and interactive visualizations of real-time environmental data. This solution demonstrates how commodity devices can promote healthier and more active lifestyles in outdoor settings.

Extensive insights into these technologies are provided in the following questions.

5.1.2 Question 2: Is the adoption of advanced Human-Computer Interaction techniques improving healthcare services?

The adoption of advanced Human-Computer Interaction (HCI) techniques is significantly improving healthcare services by enhancing user engagement, accessibility, and personalization. This is highlighted in the thesis through the integration of commodity-device-enabled AR technologies, gamification principles and IoT devices which facilitate interactive and motivating environments. For instance, mobile AR exergames motivate the users to increase their physical activity through engaging scenarios. Moreover, advanced navigation principles using AR and SLAM technology further improve accessibility, particularly for individuals with mobility challenges. Finally, commodity device sensors are utilized to assess gait metrics, with advanced haptic feedback towards better gait rehabilitation. These approaches not only engage users of all demographics, including the elderly, but also empower healthcare professionals to provide dynamic and adaptive care plans.

Examples of how the research addresses this question include:

1. **Gamified AR Exergames for Engagement**: The research incorporated gamification into AR-based healthcare applications to increase user motivation and engagement. For instance, the AR exergame platform allowed users to interact with virtual objects while performing physical activities. The gamified elements, such as leaderboards and scoring systems, encouraged consistent participation, making the process enjoyable and engaging for users of all ages. The healthcare professionals, on the other hand, could remotely monitor the health metrics and adapt care plans dynamically, showcasing how HCI techniques bridge the gap between users and caregivers.
2. **AR Indoor Navigation for Accessibility**: Advanced HCI techniques were employed in an AR indoor navigation system to guide users through complex environments such as hospitals and public spaces. By visualizing waypoints as AR arrows in the user's environment, the system provided an intuitive and accessible navigation experience. This solution particularly benefited individuals with mobility challenges, demonstrating how HCI techniques improve accessibility in healthcare and public spaces.
3. **NBS Engagement Using AR and Gamification**: The NBS application utilized advanced HCI techniques to enhance user interaction with outdoor environments. Gamified AR elements, such as badges, leaderboards, and real-time environmental visualizations (e.g., weather and air quality), were designed to promote physical activity and environmental awareness. This approach demonstrates how HCI techniques can motivate users to adopt healthier lifestyles while fostering a deeper connection with their surroundings.

4. **AR and CV for Medical Education**: The research introduced an interactive AR application that uses CV to recognize pharmaceutical packaging and display molecular compounds in augmented reality. This immersive learning tool enhances medical education by providing healthcare professionals and students with a hands-on, engaging way to explore drug properties and interactions. The integration of AR and CV technologies highlights the transformative potential of HCI techniques in creating personalized and user-centred learning experiences.

Detailed insights into the transformative role of eHI in healthcare are presented in the subsequent specific questions.

5.1.3 Question 3: How can AR, IoT and Sensors technologies engage users for Remote Patient Monitoring?

Studies were conducted showcasing the development of mobile AR solutions which facilitate increased physical activity of the users. These solutions utilize advanced Human-Machine Interaction techniques by introducing AR exergames able to run on commodity mobile devices, combined with bio signals retrieved from IoT wearables. They answer the question whether gamification can be combined with AR technology to build exergames and in turn help people be more active. An introduced AR exergame platform for mobile devices prompts the user to perform indoor activities, as part of a game series, aiming at increasing his PA and well-being. To increase the adoption of the proposed approach, and without limiting the capabilities for user interactivity and usability, a mandatory requirement was introduced: to play the game using only a single commodity product, a smartphone. The aforementioned methodology is extended to support connections with IoT wearables and IMU sensors to retrieve bio signals like steps, distance, heartrate and hand trembling measurements. The data are transmitted live to the healthcare professional which through an intelligent web platform can monitor the live activity of the patient, while playing the game. The users–players can exploit the advanced interactivity features of AR, monitor their health measurements during the game (e.g., number of steps, heart rate, and trembling of their hand), and store the results. In parallel, the professional can adapt and reconfigure the gameplay aspects, according to the condition the user and the care plan, after analyzing the results of the game sessions and the monitored activity and bio signal data. This example demonstrates the benefits of developing AR mobile exergames and remote monitoring for healthcare use cases and proves the positive impact on increasing the users' physical activity and well-being. The results from the game show that users of different ages perform well while playing the game and it increases their physical activity in a pleasant and creative way, which keeps both their bodies and minds active.

The same sensors composition can is also installed in an outdoor environment, in a Nature-Based Solution (NBS) in particular. It is a unique approach for combining these two aspects in an innovative mHealth solution by using AR - augmented reality technologies. The number of platforms which exploit the benefits of the related technologies is constantly increasing mainly due to the inherent features of AR to bring together the aspects of the physical and digital worlds. The thesis exploits the advantages of AR for creating an ecosystem with elements from the physical and digital world which will further motivate the citizens to visit the NBS areas and become more active.

Finally, commodity devices, via their IMU sensors, facilitate RPM in cases of monitoring gait-related rehabilitation procedures. This thesis introduces a pilot study that aims to evaluate the feasibility and accuracy of using mobile phone IMU sensors to detect gait asymmetries between the lower limbs of patients under rehabilitation of asymmetric gait (like stroke patients). The methodology includes positioning the smartphone in the front right and left thigh pants pockets. This study is a first step towards developing an easy way for a stroke patient, both acute and chronic, to be able to assess gait parameters at home, facilitating data acquisition, clinician telematic assessment, physical activity and exercise recommendations and improving patient adherence to rehabilitation programs.

5.1.3.1 Engaging users for increasing their physical and mental activity and RPM using AR, IoT and IMU technologies

The proposed solution combines an integrated and modular environment, state-of-the-art technologies, and tools providing benefits both for the end users and healthcare professionals who can monitor and configure the system operation. Unlike other serious games for health, this AR prototype uses technologies that eliminate the need for extra and expensive equipment, such as gaming consoles, external modules, cameras, screens, etc., and in parallel, monitor very important aspects of users' physical and mental health conditions.

An additional benefit of the mobile application is the mobility and the ability to perform AR sessions in a home environment. This is the result of a software configuration and methodology that was followed, which (continuously) takes into consideration the status of the real-world and the related physical constrains. This approach allows for a design, a user-friendly hybrid experience, which can be used easily by any user, including elders, not only by tech-savvy persons.

Another advantage is the integrated connection with a wearable that monitors the users' health data, promotes quantified-self, and provides a complete clinical view of the users' physical statuses while playing. The combination of AR and IoT is not something new; however, it is not common in a prototype for serious games in the healthcare domain. This is one of the unique characteristics of the proposed solution, which provides a ready to-use environment for AR game development, which integrates IoT sensors by design. Therefore, a holistic solution is created through which users and healthcare professionals can effectively collaborate to apply personalized care plans, improve physical activity, and promote well-being.

Along with cutting-edge technological benefits, core reasons as to why users are motivated to play the game involve its nature and the gameplay experience. The game scenarios and the multiple possible game implementations may attract the interests of users, and as a result, the chance that the game becomes obsolete is considerably reduced. In addition, the fact that game implementation and the design of the respective scenarios and challenges are coordinated by healthcare professionals provide further motivation for using the system, since the users perceive that it is tailored to their particular needs. This motivation is the goal of using the system and increasing the users' physical activity and improvement of mental status through well-designed game challenges.

The scoring and ranking system of the mobile and web apps also make the game more competitive and intriguing to play. Detailed versions of the results are accessible through the web application, which shows an extensive image of the stats and metrics with charts and pie diagrams. The fact that the healthcare professionals are actively participating in the system, assessing the results of each game and configuring the different operational and gameplay parameters are other advantages. The services that the web application offers allow the healthcare professional to continuously monitor the user while exercising and providing appropriate feedback. Apart from the results monitoring, the web application's ability to preset game sessions gives the professional the option to not only set the game parameters, but to replay game sessions and check the physical progress of the user. In addition to the activity motivation aspect, this system can be demonstrated as pleasant for the user, via retrieving important health data, which can diagnose a possible disease. The hand tremor raw data measurements, using only the device's built in accelerometer sensor, can be utilized in diagnosing tremor-based muscle or neural diseases.

The aforementioned aspects are the main novel contributions of this work, which are not currently available as part of a single offering. It should also be noted that the proposed solution not only brings together unique sets of technologies and features for gamification using AR and IoT in the healthcare domain, but also creates a modern development platform through which healthcare professionals are able to create new innovative environments to interact with their patients and monitor their health.

5.1.3.2 Cloud-Enabled Gamification to Enhance Participation in Nature-Based Solutions

The scientific contribution of the proposed NBS Gamified AR application is the utilization of computationally intelligent methods such as SLAM to create a system that will motivate users to visit the park. State-of-the-art technologies are applied and User-specific and location-related information are presented as 3D augmented objects in the user's phone screen. Advanced AR visualizations and access to additional information will only be available if the user is present at the park thus, resulting in engaging the user to visit it. The variety of content and the dynamically updated information offer a comprehensive and pleasant way of exploring and interfering with the environment. Additional information such as wind, temperature, humidity and air pollution data will offer the user a complete AR experience accommodating the users to be more active, increase their physical activity and have a greater impact on their health.

5.1.3.3 Remote gait asymmetry detection

Currently studied gait asymmetry detection methods either require the attachment of sophisticated wearable hardware like accelerometer patches at certain positions or insoles with pressure and IMU sensors. More recently they try to identify the gait through mobile phones or watches. Our proposed solution utilizes the advanced processing power and onboard sensor availability of mobile phones to identify gait cycle asymmetries. This is achieved by defining a novel procedure through the introduction of a set of guidelines, the correct following of which results in identifying gait cycles for both legs with only one IMU sensor; the one of the patient's mobile phones. Hence, the key contribution of this work is not only the development of the IMU sensor monitoring application, but the definition of the optimal recording procedure and the implementation of the user guidance to achieve following this procedure.

5.1.4 Question 4: How can AR and CV enhance medical education?

This question is answered by demonstrating studies in the combination of AR and CV for educational purposes. AR technologies are used to support education in different domains of everyday life [216] [217]. Specifically, AR solutions in healthcare use either mobile or wearable devices and glasses to support education [218] and healthcare professionals training [219]. AR technologies can also be applied for better drug management and to support patients' adherence for drug intake [220]. Moreover, AR is used for educational propositions related to chemistry and drug development [221] and can be combined with advanced image recognition technologies to build interactive AR drug encyclopedias [222]. In this context, the thesis presents a prototype application which uses AR and CV technologies for pharmaceutical substances recognition on drug packaging. The proposed application provides data visualization and information retrieval of pharmaceutical substances from PubChem database for educational reasons. Such applications may lead to healthcare professionals' and students' empowerment regarding better drug handling and management as well as to increase patient safety.

DrugEduAR application was developed as an educational tool for healthcare professionals and healthcare domain students to give easy and direct access to drug information and to enhance their knowledge related to medicine products. The key contribution in this part of the thesis is the combination of AR with Text Recognition and the connection with the PubChem database in a handheld environment available to commodity devices. The educative aspect of this work along with the working proof-of-concept prototype define a novel solution towards personalized and easy-to-use immersive intelligent eHealth systems for medical education.

5.1.5 Question 5: Is it feasible to create intelligent location-aware assistive environments?

Location-awareness is a key aspect of intelligent healthcare environments which utilize SLAM and ML. Indoor localization and navigation is a common problem, mostly in large buildings, like hospitals, where multiple floors, rooms and corridors may generate a struggling experience for the visitor. The complex internal environment, the composite architectural designs and the interference of objects and people in crowded areas, make the adoption of generic solutions hard to implement and apply, while their performance and the provided user experience do not meet the typical operational requirements. Different ways to achieve indoor localization are examined, but all require either static interventions (QR codes) or installing IoT sensors [223]. The proposed AR Navigation method for mobile devices is accomplished by displaying navigation arrows in the frontal space as part of a visualized guidance path. It is achieved by extracting image Feature Points of the space using the Phone Camera, storing them in the Cloud, resolving them in the retrospect and comparing them with newly extracted Feature Points. Thesis studies are based on the utilization of SLAM to identify surfaces on which virtual 3D navigation arrows are placed. After the system is trained, it can discover these arrows in runtime and translate them to points of interest which can be used for localization and indoor guidance. AR also supports user interactivity by creating a series of indoor waypoints to indicate a path, or other information, introducing an innovative navigation system which can adapt to support different scenarios and applications.

The thesis study aims to facilitate also the enhancement of AR navigation with a Continuous Machine Learning approach, to solve the limitation of the system's lack of flexibility in changes or environment displacements. The thesis presents a prototype approach, which is oriented towards solving the aforementioned limitation by creating an algorithm for not only assisting the AR route recording process (which is performed by the Building Administration) but also training the AR system while running by the client. This is achieved by utilizing ML in terms of optimizing the processes of AR itself and having as a practical result the improvement of the user experience in navigation and positioning applications. The naive ML procedure is running system training sessions not only in route recording time, but every time the AR application is running by a visitor. Hence, the route area is constantly captured, and the system is fed with new data after each route iteration. These data are appended to the initial ones and are simultaneously being resolved when the next user visits this route, resulting in better guidance visualization time. A prototype application implementing this procedure is developed and tested, justifying the need of intelligent solutions in the indoor navigation scenario.

AR SLAM-based navigation is also studied in crowd management scenarios of exhibition areas. The experience of visitors in exhibition areas is a key factor for the success of the exhibition and it can be considerably enhanced by using modern digital technologies and tools. Among others, the experience is affected by the number of visitors in the exhibition area, making indoor crowd management a challenging topic which crosscuts several scientific areas. The latest technological advancements include the ability of mobile devices and microprocessors to perform even heavier tasks in executing complex algorithms and data processing by utilizing state-of-the-art sensors and hardware components of the mobile devices. In the context of this thesis a crowd management algorithm and a prototype system for a museum exhibition is presented. The system operates at the network edge utilizing mobile devices as execution environments. As part of the prototype, a series of serious games is integrated. They are supplementary to the exhibits and have the goal of delaying the user before continuing to a next exhibition sector, acting in parallel as digital tools for education and information sharing for the various exhibits. Crowd monitoring is achieved by utilizing the localization ability of AR with Cloud functionality for mobile phones. Moreover, AR can be used in the serious games to offer a seamless experience by combining the exhibition site with additional content. Key contribution of this intelligent system is to demonstrate the development aspects of the system and introduce algorithms for monitoring the crowd in real time, geo-blocking the section if it is crowded, keeping the user engaged-using AR and Gamification-while waiting and prompting the user when the crowd has thinned.

5.1.5.1 AR Indoor navigation

Other AR indoor navigation studies are either proof-of-concept prototypes with limited functionality, have no user-tester friendly experience and do not meet the hardware independence standards. The between-checkpoint-distancing problem, which occurred not only in the thesis development process, but also indicated as an issue in other published works, is finally solved using the NEP algorithm. Moreover, instead of using Dijkstra or other shortest path algorithms, the proposed subsystem follows a multi-floor-centric model with support for all use cases a visitor will create. The state-of-the-art routing algorithm introducing the “room to gateway” model ensures that the correct path will be presented while optimizing the use of AR resources to the least required.

5.1.5.2 ML-enhanced AR localization

The goal of this part of the thesis is to study the effectiveness of a prototype application which introduces the use of ML algorithms for assisting AR in the scenario of AR Indoor Navigation.

Previous works approach the Indoor Navigation problem by utilizing Bluetooth beacons, WiFi antennas, RFID and generally requiring interventions at the execution site. With the proposed introduction of using AR with Cloud Anchors for comparing SLAM data between AR sessions, a new area of research and study opened.

One problem that is recognized relatively immediately by a field expert is the inelasticity of current AR navigation solutions to environmental changes in between the initial recording of an area and the moment the area is recognized by the visitor device, resulting even in not being able to identify the area at all. An example prototype that tries to overcome this issue is ARBIN. In this work Bo-Chen Huang et. al. [224] worked towards retrieving signals from installed beacons at the test site and placing the virtual arrows at the correct location based on the beacon signals. Another reference that follows the same direction is the INSAR [225], which utilizes Wi-Fi fingerprinting and phone compass to calibrate and localize the Anchors of the navigation path. Although these solutions are capable of handling changes in the environment, they require the installation of additional hardware in order to work properly. The combination of AR and ML for effectively providing evacuation navigation instructions is studied by Sang-Jo Yoo et. al. [226] but the use of ML is only limited to finding the shortest evacuation path. The localization of the user is still achieved using Received Signal Strength Indications. In addition, ML as an object detection mechanism is being used to identify artifacts of a museum exhibition and display related information via AR [227] or identify products in Retail [228]. These works utilize ML but they not to enhance the efficiency of AR in any matter. An extended literature review of the enhancement of the functionality of AR [33] highlights the possibilities that such systems can have but there is no actual implementation of any CML approach. Moreover, an implementation of ML Reinforcement Learning algorithms which effectively reduce the mobile AR computing latency in channel fading environment is proposed [229] but has no impact on the elasticity of AR to frontal scene changes. The introduction of cloud-based ML services to improve AR mobile applications orients around reducing camera drift using context-based image segmentation [230].

This research points more to a combination of Computer Vision algorithms rather than a CML approach as the proposed methods. The general conclusion that arises from comparing the characteristics of the proposed system with the related references in the literature is that the combination of CML for enhancing AR Indoor Navigation efficiency in scene changes define a scientific gab. The thesis proposed solution does not only include the general research study but also the implementation of ML algorithms to optimize the area recognition process for solving the aforementioned problem, which is the key contribution of this paper. Existing AR navigation platforms usually require two applications, the first used by the target location administration for recording AR routes and the second by the visitors for displaying the visualized guidance. The study of the thesis takes advantage of the running AR session of the visitor's device (which includes having the camera open and capturing the actual area of the route while walking) to re-capture the area and attach the newly captured data to the initial ones. In a next guidance attempt, the visitor's frontal scene will be compared not only to the initially recorded ones, but also to recordings captured by other visitors.

This algorithm is following the CML approach, which expands the data captured for a route after each navigation attempt for improving the performance of the system. Need to note here that the thesis approach is not interfering with the SLAM generated Feature Map of a navigation point, but is appending new Feature Maps at each point after a successful navigation. A prototype application was developed to test the feasibility of the thesis algorithm and several conclusions were drawn from the aforementioned test results. The results were captured by testing the application in two cases, one without modifications in the execution environment and one with modified environment and demonstrate that there is a significant decrease in the navigation elements resolve duration in both scenarios. The user experience of the visitor application is improved due to the decrease in the RD of the navigation guidance visuals and, thus, in the overall loading times.

5.1.5.3 AR gamified crowd management

Crowd management in exhibitions is a primary concern for researchers which try to provide solutions through technological advancements. Existing references in the literature include solutions which utilize IoT hardware or other static or moving equipment. The thesis proposed system promotes hardware independence and does not interfere with the exhibition environment in any way.

Moreover, instead of using AR for only rerouting the user or to just display content over QR codes or exhibits, the prototype utilizes a novel augmented guidance system which includes gamification components and methodology. While the user navigates through the exhibits, AR information pins will pop up, engaging the visitor and motivating him to stop and explore what is about to be presented. At the same time, due to the proof of presence that the Cloud Anchors offers, visitors' positions can be determined at real time and thus the current crowd status of each section.

By applying the proposed two stages methodology, by extending the augmented content length and then displaying additional AR games at the end of each section, the visitor is keeping himself engaged and also maintaining his experience at high levels by avoiding crowded sections. Concerning the acceptance of this gamification solution, results from the questionnaire show that indeed this game motivates the visitors to explore and educate themselves. It offers a variety of options and game scenarios to play and converts the waiting in exhibition areas to a comprehensive and convenient entertaining activity.

5.1.6 Question 6: How mobile solutions can increase accessibility for the impaired?

AR is studied as a standalone object detection tool that identifies exhibits and increases accessibility in exhibition areas. An important factor for such areas and especially museums, is the static equipment required for installing assistive systems, which hinders and disturbs the visiting experience. Mobile guidance systems often require the use of QR codes, Bluetooth or other hardware installations. The thesis solution offers zero interference with the museum area and the exhibits, allowing thus for optimal design of the exhibition for better experiences. There is no need to adapt the exhibition for vision and hearing-impaired people. The introduced novel Multitenant Cloud AR-based platform utilizes a mobile commodity device's localization ability to recognize exhibits for increasing accessibility in a museum environment.

The ability of AR applications to understand their surroundings and the diverse methodologies studied over the years has led to the proposal of efficient techniques for extracting depth data from a camera feed, without the need of a depth sensor and displaying the results in the immersive display environment of a mobile commodity device. This thesis proposes a system that exploits the Depth Estimation capabilities of SLAM to detect obstacles and cliffs in the user's frontal environment. A mobile application paradigm was developed which retrieves the phone camera feed and generates scene Depth-Maps before importing them to a newly designed algorithm for obstacle and cliff identification. Audio and haptic feedback is used for warnings and usability notifications. This system was evaluated and fine-tuned in real-world usage scenarios, highlighting the advanced User Experience- UX principles that were used, the ease of use from the user's side and the increase of the ease of access for the impaired individuals by the help of SLAM technology. The key contribution of this study is to demonstrate the development of a SLAM based Depth Estimation application for Obstacle Detection through the creation of a proof-of concept prototype.

5.1.6.1 Museum accessibility enhancement through AR cloud platforms

In this work a prototype AR solution is introduced for increasing system accessibility. It is capable of recognizing and interacting with an exhibition area without the need of preinstalled equipment or any sort of intervention. The Cloud Platform for AR-based POI Resolution achieves efficient object detection and object-exhibit correlation using the Services' Layer Query Engine. Run-time tests from the end-user prototype, which runs on both Android and iOS devices, show that even if the exhibition area is partially crowded, or the exhibit is scanned at an angle, the identification is performing well, while at the same time requiring an almost effortless process of training the system. Key contribution of this part of the thesis is the development of an intelligent cloud platform that can perform object and area identification without the need of any hardware intervention. It is applicable in the examples of museums and exhibitions, as it can act as an assistive tool for the impaired.

5.1.6.2 SLAM-based obstacle detection

The proposed SLAM-based obstacle detection system consists of a mobile application for commodity mobile devices which utilizes depth capabilities of SLAM to introduce a novel obstacle and cliff detection avoidance system aimed to support the visually impaired. This is a topic that actively concerns the scientific community with proposals that range from using classic hardware methods to more advanced ML solutions. A main drawback of existing solutions, which was the motivation for the current study, is the requirement of additional hardware. This hardware is either an infrastructure modification, with the addition of static cameras or sensors, or a wearable sensor that detects frontal obstacles. These solutions increase the installation cost and the execution cost, acting as a blocking factor and making the system not intriguing to the simple user. More sophisticated approaches include the training of ML models for obstacle detection which can be executed via static cameras or cameras attached to the users' head or body. The primary drawback of these installations is the lack of ease of use and the increased expense. The thesis novel solution aims at overcoming these issues by following the idea of utilizing devices that the user already owns. Another proposal would suggest incorporating ML for mobile devices; to train a model and inference on the input camera feed.

In addition, more sophisticated algorithms like OpenVSLAM and ORB-SLAM could be tested for the SLAM implementation, or Neural Radiance Field and DeepFactors for the depth estimation. These algorithms show great performance and are open-sourced, but using them draws away the attention from the scope of this research. They require a large study on the detection mechanisms, testing of multiple datasets and increased processing power of the mobile device or active internet connection to connect to a web service. The thesis work uses ARCore, a commonly used and SLAM-powered library which includes native support for depth map creation using only the phones RGB camera. Apart from the ease of development and the device compatibility, ARCore Visual-Inertial Odometry - VIO capabilities, fusing camera and IMU data, enhance robustness and offer easy adoption to commodity mobile devices like the Android phones that the prototype is designed to run. The goal of this study is not to achieve optimal SLAM performance, but rather to demonstrate a proof-of-concept prototype that applies SLAM techniques, by utilizing SLAM libraries, to create an immersive application that increases user accessibility. Hence, the primary focus of this research is the algorithmic approach of manipulating the depth map in combination with other data produced by onboard sensors. Other solutions, like LiDAR or wearable based approaches, are excluded from the study as the require devices that include advanced LiDAR scanning capabilities or additional devices, which are not in the scope of commodity devices or in the scope of cost elimination. This approach also exists in recent studies, where AR is utilized for mobile devices to enhance navigation via AR path planning which shows interesting results, but has no correlation to the thesis research. Another study is using the same ARCore Depth API but it supports only indoor environments, it does not introduce efficient object or cliff detection algorithms, it does not inform the user via haptic or audio feedback for the correct position of the device and it is more of an indoor navigation system with requirements for route recording and path planning.

The key contribution of this part of the thesis work is the overcoming of the already mentioned drawbacks via SLAM Depth Estimation, the introduction of a novel algorithm for image segmentation and obstacle and cliff detection, the targeting in ease of access and the elimination of and kind of expense. An application was developed which incorporates SLAM via AR Libraries like ARCore. Such libraries offer efficient Depth Estimation for consumer-grade devices lacking LiDAR or depth sensors. After developing the prototype, tests were performed first to fine-tune the algorithm parameters and then to test the application accuracy. The scale of the tests conducted and the type of environment that was used highlight both the feasibility of developing such tools and the usability that this approach has, backed up with both quantitative and qualitative results.

5.2 Lessons learned

Here, the insights gained during the research process are discussed, focusing on the practical and theoretical lessons that emerged throughout the development and experimentation phases.

5.2.1 Engaging users for increasing their physical and mental activity and RPM using AR, IoT and IMU technologies

An IoT Enabled AR Gamified platform for commodity devices can demonstrate substantial impacts in the healthcare domain by facilitating the development of innovative interventions as part of a personalized care plan. The proposed AR system enables the provision of advanced remote monitoring capabilities with the active participation of healthcare professionals who can change the system parameters during operation and also create new game scenarios. The proof-of-concept prototype implementation validates the synergy of the utilized technologies and the capability of offering the aforementioned functionality with commodity devices.

The content of an NBS AR application example in both visual and informative aspects may considerably improve the engagement of the users to visit the park often and which in will have a positive impact on their health. By providing the user with not only his fitness data but also comparisons to other users in the context of a tailor-made gamification scenario, as well as by visualizing the data in a blended with the real environment way, it highly increases their willingness to repeat their visits and achieve a better personal “badge”. Augmented information about the current, previous, or future attractions of an NBS is a factor that will engage the users to make a visit. Navigation and routing will also help participants to find their paths and all visitors to not miss visiting any important to them space. What makes this approach unique is the requirement of the user presence in order to get access to this information. By requiring presence, motivation to perform a visit in the park is increased.

5.2.2 Assisting the impaired through handheld SLAM-based solutions

Mobile commodity devices already achieve satisfactorily results when they are required to run intensive tasks, such as image processing, data transmission and human-computer interaction.

These advantages can be utilized to improving the quality-of-life and accessibility of impaired people while at the same time reducing their social exclusion. The utilization of a Cloud Platform for AR-based POI Resolution unlocks possibilities for further research in the field of static area identification and proof-of-presence.

The positive outcome from the SLAM-based obstacle and cliff detection system of the thesis lies both in the effectiveness of the algorithm execution and the user ease of access, as highlighted in the results of the thesis study. The system was tested under various environments which include both indoor and outdoor spaces with lighting conditions also taken into consideration. Results showed that the system runs smoothly, and although a minor performance impact is present for low-end devices, the primary goal of identifying the obstacles is achieved with minor to zero errors. The thesis study demonstrates encouraging examples towards optimizing Human-Machine Interaction techniques for remote support of the visually impaired and increasing their quality of life.

5.2.3 Introducing location-aware mobile intelligent systems for navigation and localization

Advancements in Computer Vision technologies along with the evolution of microprocessors, sensors and cameras form a rich set of assets which facilitate the implementation of innovative solutions for indoor localization and navigation. The proposed AR navigation solution of the thesis not only improves and expands the AR Anchor "checkpoint" navigation approach, but also introduces a new routing algorithm, offers interoperability and platform independence.

AR Navigation applications are being studied for solving the Indoor Navigation problem without capturing the case of modifying the interior environment. The thesis identifies this problem and proposes an ML algorithm for the AR workflow, tested in a real user scenario.

The demonstrated innovative techniques have been integrated at a state-of-the-art prototype application in which the ML algorithm acts as a higher level of intelligence that optimizes Augmented Reality for indoor recognition. Hence, the contribution of the thesis is the combined use of ML algorithms as an extra layer of intelligence above the utilization of Augmented Reality.

Gamified crowd management is studied in this research and the development of a proposed state-of-the-art prototype utilizing AR and gamification is presented. The system is checked for feasibility and stability but as a future extension, a more extensive study in a larger scale scenario can be conducted. Results from the visitors viewing or playing the game show that it is an accepted technological solution and they would like to see it in larger scale scenarios.

5.2.4 Facilitating medical education through AR and CV

The combination of AR and CV in the form of utilizing CV do identify points of interest on the screen before visualizing related information via 3D AR content is a primary aspect serving the goal of the thesis. Via the drug identification proof-of-concept paradigm, a lesson that is learned is that combining AR and CV is not only feasible but the result provides a more personalized and immersive experience, engaging the user to serve the pre-defined goal using commodity hardware running intelligent applications.

5.3 Main difficulties and methods to overcome

This subsection reviews the main challenges encountered during the study and presents the strategies and methods adopted to address them.

5.3.1 Engaging users for increasing their physical and mental activity and RPM using AR, IoT and IMU technologies

In the context of the IoT AR Exergame, a problem that raised during the development of the system was the overlapping Anchor problem, as the system initially was attaching Anchors randomly in the frontal scene. In order to avoid overlaps, an anchor placement algorithm was introduced, based on experimentation in real user environments, such as living rooms, offices, gardens and kitchens. Figure 44 illustrates the flow of the algorithm, entitled “Anchor Overlap Avoidance System”, which is executed for each question. The answers of a question along with their data (labels, assets, etc.) are stored in a list in the system memory while the AR session is initialized and plane detection starts. For each answer, the algorithm first obtains a random possible location on one of the detected planes. Then, it checks whether this location fits the following criteria:

- Distance from camera is greater than 2m;
- Distance from camera is less than 7m;
- Distance from the nearest anchor is greater than 2m;

If these constraints are met, the anchor of the answer is placed, and the corresponding 3D model is benign rendered.

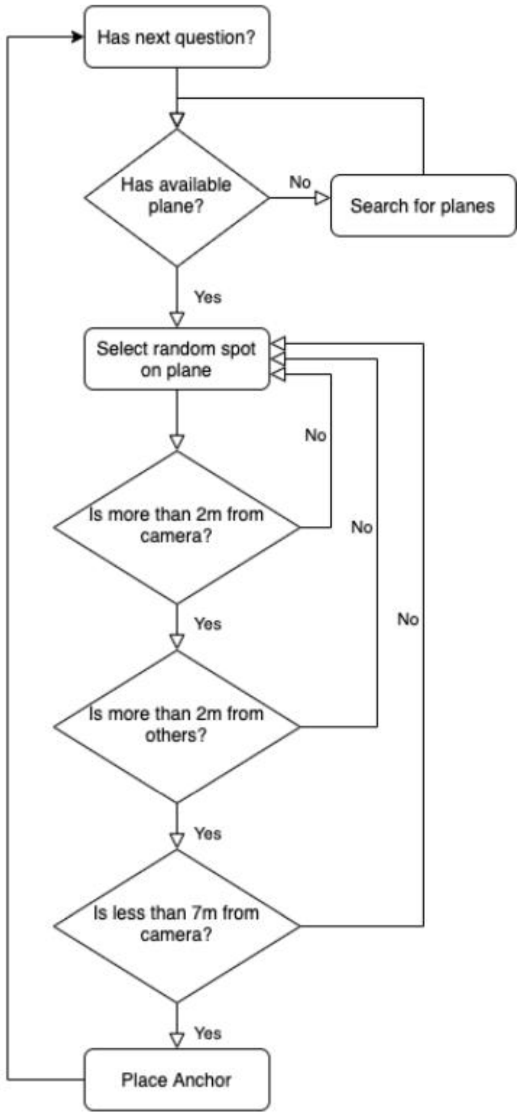

Figure 44: The flow of the Anchor Overlap Avoidance System

A limitation of the NBS AR Gamification system is the efficiency of the SLAM, as the experimentation site is an outdoors space. The environment can easily change and break the SLAM system. Towards this issue, the utilization of GPS-enabled Anchors can be potentially tested for achieving the same functionality.

In the proposed Gait Asymmetry Detection system, the thesis focuses on providing a gait asymmetry assessment experience at home without the need for in-person monitoring by a healthcare professional. Some limitations arise from this scenario, all of whom rely on the correct set-up of the application. Since there is no way to monitor the two legs simultaneously, without additional hardware, the user must follow strictly the instructions and needs to perform the two 10-second tests trying to avoid steep turns. If the phone is not inserted correctly the results may not be correct. Moreover, the size of the pocket and the weight of the device play a role in the system outcome. Lighter devices in larger pockets may insert noise in the data, which is produced from the hits of the phone in the leg surface. Last, light training of the healthcare professional is required to understand the graphs.

5.3.2 Assisting the impaired through handheld SLAM-based solutions

This subsection reviews the primary challenges encountered in developing handheld SLAM-based solutions for assisting the impaired, including exhibit recognition in museums and obstacle detection for visually impaired individuals. It outlines the methods employed to address these challenges, such as optimizing system parameters, addressing hardware limitations, and improving user accessibility and experience.

5.3.2.1 Museum accessibility enhancement through AR cloud platforms

A limitation of the Multitenant AR accessibility cloud platform is the requirement of guiding the exhibition staff in case of a need for re-training the system. A well-structured admin application is needed so it can be easy for a non-field related person to train the system. Another limitation is the 40 simultaneous Anchors resolve limit, due to the used library specifications. To solve this, an advanced key-anchor approach is proposed, which instead of identifying one Anchor per exhibit, it identifies first a key Anchor that indicates the specific part of the exhibition, and, then, identifies the exhibits. This proposal limits down the simultaneous resolves.

5.3.2.2 AR SLAM-based obstacle detection

A problem that raised since the initial stage of the development of this system was the optimal thresholds determination, since the depth map covers the entire screen of the phone and may include sections that can produce FPs or TNs.

To determine the optimal thresholds, Low Bounds, High Bounds and Width Percentage were calculated after a series of measurements under real usage scenarios. In addition, the maximum Tilt Angle was measured to verify the correct device orientation.

5.3.2.2.1 Low Bounds

The Low Bounds parameter defines the limits that decide whether an obstacle is identified, if the average depth of the cell is lower than this limit. It contains four values, one for each row of the grid. For the Low Bounds, a total of 52 tests were performed, 13 for each of the four rows with values differing between [500 mm, 1000 mm, …, 6500 mm]. The average duration of the tests was 10 minutes at a path that included 15 obstacles for each limit.

For the top row (Row 0), the optimal obstacle avoidance was found in Low Bounds value of 2500 mm. While all obstacles are identified at Low Bounds 4000 mm, the application is also notifying the user for obstacles that do not exist. The TP, FP, FN values are presented in Figure 45 while Precision, Recall and F1-Score are demonstrated in Figure 46 with Low Bound distance varying between 500 mm and 6500 mm with a step of 500 mm.

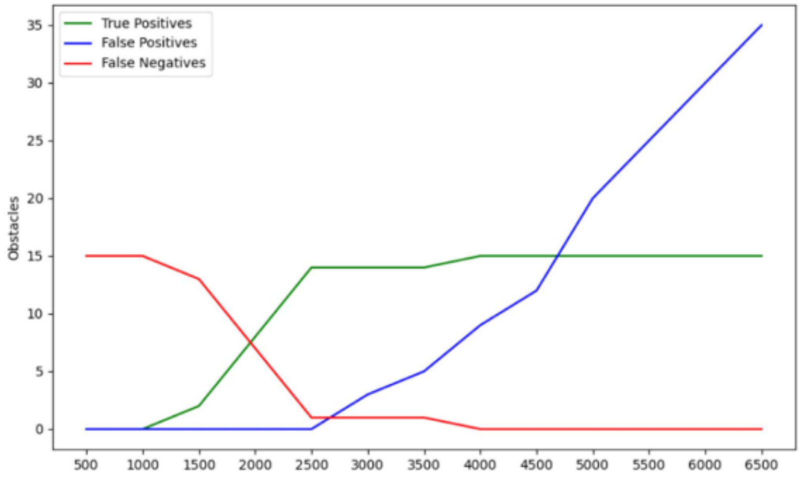

Figure 45: This chart displays True Positive, False Positive and False Negative values of Row 0. Y-axis represents obstacles between 0 and 35 and X-axis represents distance to obstacle, between 0 and 6500 mm, with a step of 5 obstacles and 500 mm accordingly. Peak performance is identified at 2500 mm, where there are 0 FPs, 0 FNs and 15 TPs.

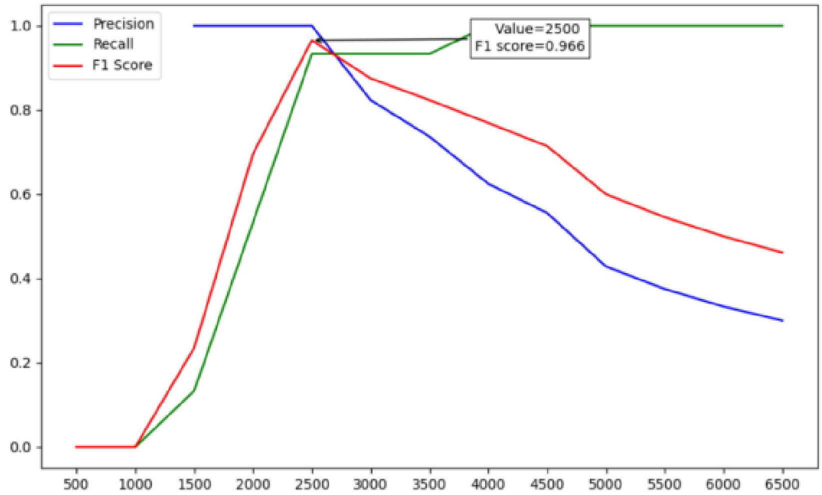

Figure 46: Precision, Recall and F1-Score metrics of the Row 0. Y-axis represents the scores while X-axis represents distance to obstacle, between 0 mm and 6500 mm. Peak performance is identified at 2500 mm, where F1-score is the closest to 1.

Following the same process for the second Row (Row 1), the optimal Low Bounds value is 5000 mm, 4500 mm for the third Row (Row 2) and finally 2500 mm for the last Row (Row 3). The metrics of these values are demonstrated in Table 18. An example of Obstacle detection using Low Bounds optimization technique is shown in Figure 47.

Table 18: This Table Demonstrates the Optimal Low Bounds Values for Each Row and the Respective True Positives, False Positives, False Negatives and F1 Scores

Row	Low Bound	TP	FP	FN	F1-Score
0	2500	15	0	0	0.966
1	5000	13	1	2	0.897
2	4500	15	2	2	0.938
3	2500	15	1	0	0.938

Figure 47: Example showing the system successfully identifying the parked car using Low Bound metric of 4500. The parked car is identified at the bottom left side of the grid, where cells are highlighted with red color.

A difficulty was identified when trying to identify objects for Row 1. This is due to the low width of obstacles in combination with large depth distance of the environment. The use of average is balancing the low values of the obstacle with the large values of the background. To overcome this, a modification of the algorithm is performed on the cells second Row with the average computation mechanism performing first an ascending sort of the depth values. Then, a portion of the cell Depth-Map is selected for calculating the average. This portion is defined by the Mean Percentage attribute. The sort ensures that the points that are included in the average calculation are the ones with the lowest values. 10 tests were performed with Mean Percentage values between 10 and 100 (step 10), and 5000 mm Low Bound limit. The value of 60 achieved the best F1-Score (0.968) which is larger than the previous 0.897 value. The screenshots of Figure 48 demonstrate the second-row middle cell that is unable to identify an obstacle on the left, and successfully identifying the obstacle on the right.

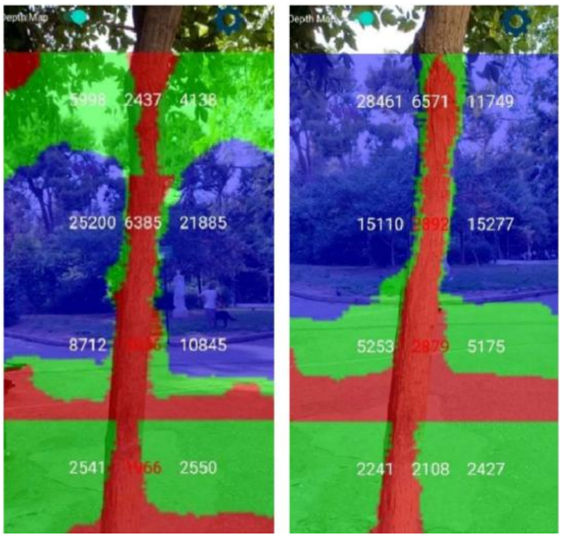

Figure 48: Utilization of Mean Percentage: The Second Row is unable to identify the obstacle (Left) due to the tree been too thin. To overcome this, the Mean Percentage of the middle cell is calculated (Right) which provides efficient detection.

5.3.2.2.2 High bounds

The High Bounds parameter defines the limit of cliff existence decision, where an average distance is larger than this value. Only the bottom row (Row 3) is used since the world at the rest rows is not in the examined field of view. To calculate the best High Bound variable, 13 tests were conducted with the same methodology (500 mm to 6500 mm range and 500 mm step). All cliffs were successfully identified until High Bound 5000 mm. However, for the relatively small values, the FP level is high and, hence, F1-Score is lower. The optimal value was identified at 5500 mm with an F1-Score of 0.889. An example of the High Bounds optimization technique is shown in Figure 49.

Figure 49: Example showing the system successfully identifying the stairs going down. Stairs are identified at the bottom left side of the grid with distance labels highlighted with blue.

5.3.2.2.3 Width Percentage

Not full width of the screen is required to successfully identify objects and cliffs. If, for reference, a wall exists at the far-left side of the screen, but the user is not facing towards it, it is not a dangerous obstacle. Hence, a part of the input camera feed should be ignored. The Width Percentage value defines the percentage of the screen that the grid will be placed. Values between 10 and 100 were tested with the value of 60 being the best. Figure 50 indicates obstacles in the left column when using value 100. The finalized version which uses the 60% of the screen shows no obstacles, which is the correct.

Figure 50: The initial example (Left) wrongly indicates obstacles on the far left of the scene while the final version (Right), which uses the 60% of the width, indicates no obstacles. Obstacles are identified where the distances are highlighted with red color.

Maximum Tilt Angles A device orientation is quantified as a vector of X, Y and Z axis values. The vertical rotation of the device is provided via the Y axis value of the rotation rate vector of the IMU. The values −10 and 20 were selected for minimum and maximum allowed angle along with an absolute value of 20 for the Z axis. If the device is running outside of these limits, a system message is displayed along with haptic feedback as shown in Figure 51.

Figure 51: Message (in Greek) for indicating that the device has wrong orientation along with haptic feedback is provided when the device is facing down (Left) or up (Right). The translated text: "Please orient the device facing forward".

Worth to mention that the approach of dynamically moving the grid of the Depth-Map was quickly abandoned as the user was not "forced" to maintain the device at a certain orientation, allowing for irrational orientations (e.g. device facing the ground).

5.3.3 Introducing location-aware mobile intelligent systems for navigation and localization

This subsection discusses the challenges faced in developing location-aware mobile intelligent systems, including AR-based indoor navigation, ML-enhanced AR localization, and gamified crowd management. It highlights limitations such as hardware compatibility, SLAM performance, environmental changes, and system scalability, while detailing the methods employed to overcome these challenges, such as adaptive algorithms, resource-efficient designs, and user-centric approaches.

5.3.3.1 AR Indoor Navigation

A significant limitation of the studied AR indoor navigation system is the requirement of ARCore compatible devices. Concerning the efficiency of the SLAM, if a corridor or place does not contain any special characteristic rather than plain walls or is filled with people, localization will take longer to process. Needs to be noted, though, that the aforementioned limitations are directly bound to the quality of the Anchor placement procedure. Low GPS / Cellular coverage or the lack of precision in small displacements is a deterrent factor of using these technologies while installation of transmitters (sensors) can be expensive and slow down the integration of such a system. Although existing studies try to follow a SLAM oriented direction, there are many occurring limitations, obstacles and restrictions this work is overcoming.

5.3.3.2 ML-enhanced AR localization

A primary limitation of this approach was the ARCore library 40 simultaneous anchors resolve limitation. Hence, the Anchor resolve point system was introduced which facilitates an intelligent "good" Anchor provision over "bad" Anchors, which are disposed. The system needs to be tested in larger scale scenarios and more complex and multi-story buildings.

5.3.3.3 AR gamified crowd management

Due to the ARCore limitation of only 40 simultaneous Anchor resolve processes, a top-down approach has been followed: at first key anchors that correspond to the sections are resolved and, then, only the Anchors that are required for each individual section are resolved. This routing algorithm not only overcomes the software limitation but also facilitates a more efficient localization and a faster end-user experience increasing the user engagement.

Following the experimentation in the test exhibition area, it is clear that this system will not work if not a critical portion of the visitors are using the app; however, for the purpose of this study it is taken for granted that all users are using the application for guidance in the exhibition. In addition, the quality of the 3D models that are used plays a big role in the system performance. From the 3 LOD stages in each model, the optimal solution is to stick with LODs that offer a playable performance in all tested devices. Another solution to this would be to either give the user the ability to select the quality of the graphics (low, medium, high), or to automatically set the graphics based on the running device.

5.3.4 Facilitating medical education through AR and CV

The combination of AR and CV presents unique opportunities for transforming medical education through immersive and interactive learning experiences. While the proposed system, *DrugEduAR*, demonstrates feasibility and applicability, the development process revealed several limitations and challenges that need to be addressed to further enhance its functionality and scalability. This subsection elaborates on the primary challenges encountered during the development of the AR-based drug identification system and the methods and strategies to overcome them, while also discussing potential areas for improvement.

The knowledge base is currently limited to PubChem, which may not include region-specific pharmaceutical products. Additionally, the system's text recognition is primarily optimized for English, reducing its usability in non-English-speaking regions. Interactivity is also limited, as users can only view static 3D models and basic information without deeper engagement, such as simulations or quizzes. Furthermore, the reliance on commodity mobile devices means that performance can vary significantly, particularly on low-end devices with limited processing power or lower-quality cameras.

To address these challenges, the system can integrate additional databases, such as DrugBank or regional pharmaceutical registries, ensuring broader coverage. Multilingual OCR engines and machine translation APIs can enable text recognition in diverse languages; while pre-processing algorithms can improve recognition accuracy in low-quality conditions. Enhanced interactivity, such as dynamic 3D models, simulations, and quizzes, can make the system more engaging and educational. Performance scaling techniques, like adaptive model rendering and lightweight algorithms, can ensure compatibility with low-end devices. These enhancements will make *DrugEduAR* a more robust and widely applicable educational tool for healthcare professionals and students.

5.4 Bringing the research into real life scenarios

The broader context in which the research findings may be applied is considered here, situating the developed approaches within real-world healthcare scenarios and related domains.

5.4.1 Engaging users for increasing their physical and mental activity and RPM using AR, IoT and IMU technologies

The thesis, by utilizing IoT, AR, cloud, and web technologies, proposes a prototype that, aside from being a physical activity exergame, also monitors the user’s current measurements, provides the doctors with real-time health data, and offers them the option to pre-define and remotely control the game. Furthermore, it is hardware independent and may operate on commodity—and, in most cases, already pre-owned— devices, maintaining very low ownership costs. Overall, it can extend the user’s knowledge base and it offers a fascinating way to improve well-being in the general concepts of quantified self-assisted living.

The NBS AR Gamification proof-of-concept prototype is developed and is motivating participants to visit pocket parks. The prototype is tested at a real pocket park in Piraeus, Greece. Results showed great applicability but the anchor positioning subsystem is vulnerable to area changes.

5.4.2 Assisting the impaired through handheld SLAM-based solutions

The AR exhibit identification system is applied at the Aristotle Museum of Thessaloniki, as part of a sign language related project. The application successfully identifies the exhibits and offers to the impaired visitors a more accessible and engaging experience.

The mobile gait asymmetry detection tool was deployed and tested via simulating paranormal gait events. Results showed that the system is applicable and needs to be tested in larger scale.

The development of AR applications for mobile devices that utilize the AR depth capabilities to identify obstacles and cliffs for both indoor and outdoor environments is highlighted in the thesis. The developed a prototype application is utilizing ARCore Depth API for extracting Depth-Maps from the frontal scene and identifying obstacles via a newly introduced algorithm. Audio and haptic feedback warn for upcoming obstacles and notify to fix the device orientation if the phone is not facing the correct direction. This solution increases accessibility, as it can be executed at any place, and decreases expense, as it is running on commodity devices.

5.4.3 Introducing location-aware mobile intelligent systems for navigation and localization

The AR indoor navigation application entitled "UNIPI: AR Experience" highlights the development process of a complete functional system with a Hybrid AR Platform and client application, able to apply in real conditions providing satisfactory results while maintaining the cost and interventions at the lowest level. The system is deployed at the experimentation site and tested under real world scenarios.

An extension of the aforementioned system integrates ML to the AR localization processes and is also installed at a university environment. This system has the added functionality of identifying changes to the frontal space and retraining the system to include these changes.

The prototype AR gamified crowd management system is successfully applied at a real usage scenario proving the applicability and usability. Feedback from the audience shows great interest and user engagement.

5.4.4 Facilitating medical education through AR and CV

The drug identification mobile application is titled “DrugEduAR” and is applied in the field of identifying the drug of Paracetamol. The results highlighted that the system is applicable due to the wow factor of the AR experience and the advanced intelligence that CV provides.

5.5 Thesis Extensions and Future work

The final subsection outlines directions for future research, suggesting how the presented work can be further extended and refined to address remaining challenges and explore new opportunities.

5.5.1 Engaging users for increasing their physical and mental activity and RPM using AR, IoT and IMU technologies

In future extensions of the IoT AR Exergame platform, additional parameters may be supported in order to provide a more detailed view of the users' health and cognitive status to the healthcare professionals. This includes, among others, integration with affective computing frameworks to assess the users' emotional status. Other AR and general computer vision engines may be examined and tested in order to determine whether they are capable of handling such use cases. The gameplay can be further improved, allowing for more advanced interactions with the real world, which will be exploited in the development of more complex game challenges and scenarios. In collaboration with healthcare professionals, the challenges can be enhanced to be aligned with the care plan of the users, and rules for the dynamic adaptations of the game parameters, based on the care plan and the monitored results, will be implemented. As part of this extension, existing implementations for recommendations for quantified-self applications can be integrated. Finally, multi-user operations may be supported in the same physical location, as well as remotely, for providing even better user experience and more exciting gameplay.

Regarding the NBS AR Gamified system, the primary limitation of which being the SLAM efficiency, the thesis proposes the utilization of GPS-coordinated Anchors and the study on whether their precision is high enough to offer the same visual result.

5.5.2 Assisting the impaired through handheld SLAM-based solutions

Further extensions to the exhibit recognition client library and the AR Multitenant cloud platform are foreseen to enhance the accuracy of the system and the time required to identify the POIs even in highly complex and crowded environments. Moreover, the scalability of the system needs to be assessed, in larger areas. Other AR libraries or AR glasses need to be tested also.

Future extensions of SLAM-based obstacle detection systems may include the execution of this algorithm in different scenarios and the addressing of some limitations like the camera motion blur or the low contrast obstacles. The utilization of ML or NN-based approaches to identify the type of an upcoming obstacle (e.g. tree, car or stairs) can also be studied. The integration of the thesis system to a full visually impaired guidance system with path or road detection is another future extension with increased accessibility factors. Other Depth Estimation libraries, like the aforementioned ones, should be tested, either running on the device or in the cloud. Finally, iOS or web implementation would increase the supported devices.

5.5.3 Introducing location-aware mobile intelligent systems for navigation and localization

Future extensions of AR indoor navigation systems may include a wider system usage monitoring. Moreover, other cross platform AR frameworks can be considered (e.g. Unity AR Foundation) and compared with the current implementation. SLAM's environmental understanding provides indication of a device's deviation from a route path. For people with special needs and particularly the visually impaired, a voice command module indicating directions and deviations is a possible future proposal. AR navigation systems can be experimented in other scenarios with limited signal coverage and short distances between targets (e.g. in a museum or hospital). Considering the route creation procedure, an extension of the system is expected to further automate this process, and possibly eliminate completely the need of an experienced system administrator, either by integrating this functionality to an AI tool which will be integrated into the Creator Module.

As a future direction of the ML-enhanced AR localization extension, the creation of an ML model that will inference the quality of an Anchor recording before uploading can be considered. It will work in both Administrator and Client applications scenario, for the first to guide the administrator to make a better area scanning and for the second to exclude the addition of Anchors that will not likely have a successful result. Moreover, the system needs to be tested in a larger scale scenario, and include also navigation for precise outdoor cases, which do exist in the current test site. Finally, other SLAM algorithms should be examined and compared to the currently used library for efficiency and sensitivity to environmental changes.

A future scenario of the AR gamified crowd management system, which also serves the issue of requiring all visitors to use the app, is to utilize the open camera feed that the visitor has and to combine it with other CV algorithms for crowd counting. Moreover, other more sophisticated AR games may be introduced, and more models may be inserted to check the performance and user engagement of the system.

5.5.4 Facilitating medical education through AR and CV

Future work of the drug identification system includes the further system development with additional features so users could choose the nature of the received information as well as the in-app implementation of tests and questionnaires for users' knowledge review assessment.

6 Conclusions

This thesis demonstrates the significant potential of Computational Intelligence (CI) in remotely supporting patients and revolutionizing healthcare delivery systems. By leveraging edge technologies, such as AR, CV, IoT and SLAM, the thesis introduces innovative, scalable, cost effective and hardware independent solutions.

6.1 Key Findings

The key findings of the thesis are summarized below, based on the defined pillars:

Finding 1: AR, IoT, and IMU sensor technologies can facilitate efficient and engaging RPM

Gamified AR exergame platforms demonstrated the feasibility of using commodity devices for serious health applications without the need for specialized or expensive hardware. The integration of AR and IoT in NBS engages users in outdoor physical activities, improving health outcomes while fostering engagement with urban green spaces via gamification solutions. The study on gait asymmetry detection enables stroke patients and other mobility-impaired individuals to assess their gait patterns at home with minimal intervention.

This Key Finding matches **Pillar 1.3.1** since both focus on using AR, IoT, and IMU technologies for engaging users in physical and cognitive activities and enabling Remote Patient Monitoring (RPM). It answers Questions 1, 2, and 3, as the pillar states, and Question 5 as it extends these solutions to outdoor environments like NBS, which involve location-awareness.

Finding 2: Accessibility for the impaired is increased through handheld SLAM-based solutions

The AR-based exhibit recognition system's multitenant cloud platform enables efficient exhibit identification without requiring static installations or QR codes, ensuring scalability and adaptability across diverse environments, providing an accessible and hardware-independent solution for improving the experience of visually and hearing-impaired visitors in museum scenarios.

The SLAM-based obstacle detection system identifies obstacles and cliffs in real-time for visually impaired individuals, showcasing the use of depth estimation and novel segmentation algorithms. The system relies on commodity devices and, thus, ensures accessibility and cost-effectiveness.

This Key Finding aligns with **Pillar 1.3.2**, as it focuses on SLAM-based solutions for improving accessibility, particularly for visually or hearing-impaired individuals. It includes obstacle detection, navigation, and AR-based exhibit recognition systems for assistive environments. It answers Questions 1, 2, 5, and 6, as the pillar explicitly addresses these aspects.

Finding 3: Indoor localization-aware mobile solutions can facilitate efficient and adaptable navigation

The AR indoor navigation system demonstrated the practicality of using SLAM for indoor localization without requiring infrastructure modifications. The introduction of the NEP algorithm and a multi-floor routing model enhanced the system's usability.

The ML-enhanced AR extension of the previous prototype enables the system to adapt to environmental changes, ensuring robustness and scalability in real-world applications and addressing critical limitations of existing AR navigation systems by introducing a Continuous Machine Learning (CML) algorithm.

The AR gamified crowd management system provides an innovative solution to reduce overcrowding while enhancing the visitor experience by effectively utilizing gamification and augmented content to manage visitor flow in exhibition areas.

This Key Finding corresponds to **Pillar 1.3.3**, which focuses on AR and SLAM-based navigation, localization, and crowd management systems. It highlights indoor navigation, Continuous Machine Learning (CML) for adaptability, and gamified crowd management, which are core aspects of this pillar. It answers Questions 1, 2, and 5, as stated in the pillar.

Finding 4: Medical education can be advanced through mobile AR and CV solutions

A mobile AR application was developed to recognize pharmaceutical products using computer vision (CV) algorithms, displaying molecular compounds and retrieving drug information from external databases like PubChem. The application serves as an immersive educational tool for healthcare professionals and students, improving understanding of drug properties and interactions. These findings underscore the potential of AR and CV to revolutionize medical education and empower healthcare professionals with innovative learning tools.

This Key Finding directly matches **Pillar 1.3.4**, as both focus on the use of AR and CV technologies for educational purposes, such as recognizing drug packaging and visualizing molecular compounds. It answers Questions 1, 2, and 4, as the pillar specifies.

6.2 Addressing the research questions

The research questions that were first introduced in the Introduction section were later divided into separate topics which answer them.

1. Question 1, “Can commodity mobile devices facilitate efficient assistive living?”, is answered by **all Key Findings** and highlights its importance towards the thesis goal.
2. Question 2, “Is the adoption of advanced Human-Computer Interaction techniques improving healthcare services?”, is also related to all research activities of the study and is addressed by **all Key Findings**.
3. Question 3, “How can AR, IoT and Sensors technologies engage users for Remote Patient Monitoring?”, is answered by **Key Finding 1**.
4. Question 4, “How can AR and CV enhance medical education?”, is addressed by **Key Finding 4**.
5. Question 5, “Is it feasible to create intelligent location-aware assistive environments?” is addressed by **Key Findings 1, 2 and 3**.
6. Question 6, “How mobile solutions can increase accessibility for the impaired?”, is addressed by **Key Findings 1 and 2**.

6.3 Broader Implications

The thesis establishes that intelligence, when applied thoughtfully, can address systemic challenges in healthcare:

- It enhances accessibility through hardware-independent solutions that leverage existing commodity devices.
- It is cutting costs associated with specialized hardware and infrastructure modifications.

- It increases user engagement and adherence to care plans through gamification and personalized applications.
- It proposes scalable and adaptable systems that can be deployed across multiple environments, from homes and parks to hospitals and museums, to serve a healthcare goal.

In conclusion, this thesis demonstrates that eHI, when combined with AR, CV, IoT, and SLAM, and via the proposed algorithmic approaches, has the potential to transform electronic healthcare into ambient assistive living scenarios. The real-world challenges that are addressed via innovative, user-centric, cost-effective and hardware independent solutions contribute to advancements in the state of the art in the intelligent healthcare technology while the findings of this thesis open up several avenues for future research, development, innovation and broader societal impact.

7 Publications within the framework of this thesis

Within the activities of the thesis, the following articles have been published in international scientific journals:

1. “An IoT-enabled platform for the assessment of physical and mental activities utilizing augmented reality exergaming” [231].
2. “Continuous machine learning for assisting AR indoor navigation”, published at the “Springer Nature: Computer Science” [232].
3. “On the utilization of SLAM for obstacle detection in commodity mobile devices” [233].

Furthermore, the following articles have been published in international scientific conferences:

1. “On the development of augmented reality based exergames for assessing human activity and cognition on mobile devices” [234].
2. “Integrating AR and IoT services into mHealth applications for promoting wellbeing” [235].
3. “Exploiting augmented reality and computer vision for healthcare education: the case of pharmaceutical substances visualization and information retrieval” [236].
4. “Utilizing AR and Hybrid Cloud-Edge Platforms for Improving Accessibility in Exhibition Areas” [237].
5. “Augmented Reality for Indoor Localization and Navigation: The Case of UNIPI AR Experience” [238].
6. “On the Utilization of Commodity Devices for Efficient Gait Asymmetry Detection” [239].
7. “Gamified Crowd Management Utilizing AR and Computer Vision on the Edge” [240].

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