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Doctoral Thesis

– SUMMARY –

SENSOR-BASED APPLICATIONS FOR THE VISUALLY IMPAIRED

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GENERAL INTRODUCTION

Given the increasing global prevalence of visual impairments, over 2.2 billion people are affected worldwide according to the World Health Organization, access to assistive technological solutions has become a strategic priority for social inclusion. Loss of visual acuity negatively impacts individual functionality in physical environments, while modern assistive technologies offer practical alternatives aimed at restoring personal autonomy, especially in urban and institutional spaces.

This doctoral thesis addresses this societal need by developing and validating autonomous, reliable, and accessible assistive devices intended for people with visual impairments. The research adopts a user-centered, pragmatic approach, aiming to compensate for the lack of visual information through auditory and tactile channels, using ultrasonic and optical sensors integrated into microcontrolled systems. Simultaneously, a mobile application is designed for Romanian banknote recognition, employing machine learning (ML) techniques to support users in financial transactions.

The scientific endeavor is multidisciplinary, incorporating principles from electronic engineering, applied informatics, signal processing, artificial intelligence, and digital accessibility. The methodology includes rapid prototyping, algorithmic performance evaluation, iterative testing in real-world scenarios, experimental calibration, and validation through direct interaction with the target group (students from the Special School for the Visually Impaired in Cluj-Napoca).

This thesis offers a significant practical contribution by proposing replicable and scalable solutions with low costs, ease of use, and the potential to replace or complement commercially available assistive technologies, which are often prohibitively expensive. These solutions aim to enhance users' quality of life by improving spatial orientation, contextual recognition, and independent interaction with their surroundings.

CHAPTER 1. MOTIVATION FOR CHOOSING THE RESEARCH TOPIC

Visual impairments are among the most common and debilitating disabilities worldwide, directly affecting individuals' ability to integrate socially, move independently, access education, and maintain personal autonomy. According to recent estimates from the World Health Organization (WHO), approximately 2.2 billion people suffer from various forms of visual impairment, with at least one billion potentially benefiting from corrective interventions or assistive technologies. In Europe, data from the European Blind Union (EBU) show that approximately 30 million individuals have significant visual impairments, particularly affecting the population over 60 years of age.

This public health challenge is exacerbated by the global increase in life expectancy, the rising incidence of chronic degenerative eye conditions (e.g., cataract, glaucoma, macular degeneration, diabetic retinopathy), and limited access to ophthalmological services in many regions. Additionally, ocular trauma and accidents frequently result in irreversible blindness, especially among the working-age population. Affected individuals, whether congenitally blind, progressively visually impaired, or suffering from acquired blindness face severe challenges in maintaining functional independence, particularly in unfamiliar or poorly equipped environments from an accessibility standpoint.

In this context, the development of personalized technical assistance solutions has become a strategic necessity to ensure social equity and the inclusion of visually impaired individuals. However, most currently available commercial technologies (e.g., OrCam and eSight smart glasses, sensor-integrated white canes, advanced mobile apps) are either prohibitively expensive or insufficiently adapted for indoor navigation requirements. Many of these solutions rely heavily on constant smartphone use, internet connectivity, or extended training and adaptation periods—factors that limit their adoption among elderly users or those with comorbidities.

This doctoral research is grounded in identifying a real, pressing, and unmet need: the development of autonomous, portable, financially accessible, and easy-to-use devices to assist spatial orientation for blind individuals in indoor environments. The choice of this research direction was also supported by direct observations made in collaboration with the Special School for the Visually Impaired in Cluj-Napoca, where it was found that suspended obstacles (open windows, furniture, pipes, etc.) could not be detected with a classic white cane. Furthermore, user feedback indicated the necessity for solutions that do not interfere with other senses and allow for customized warning messages.

Another key factor motivating the topic is the need to democratize assistive technologies. Given that existing solutions often exceed €5,000–6,000 per unit, there is a compelling imperative to propose alternatives that can be constructed for under €25 without compromising essential functionality. This goal can be achieved using ultrasonic sensors (HC-SR04), microcontroller platforms (ATmega328), simple audio modules, and efficient signal processing algorithms calibrated rigorously in controlled test environments.

The scope of this work extends beyond obstacle detection. An additional relevant dimension involves integrating contextual recognition features, such as color identification or banknote classification. For the latter function, a mobile Android application based on convolutional neural networks (CNN) was developed, utilizing the smartphone camera to audibly announce the value of a Romanian banknote. This application complements the suite of proposed solutions and demonstrates the practical applicability of AI technologies in digital accessibility contexts.

Therefore, the motivation for this topic arises from three core needs: **Social** – supporting a vulnerable population group; **Technological** – leveraging low-cost embedded components and adaptable sensors; **Scientific** – developing, testing, and validating a complex system with demonstrable performance.

The thesis stands out for its applied, interdisciplinary character and for directly involving end users in the iterative device design and refinement process.

CHAPTER 2. OBJECTIVES OF THE THESIS

This doctoral thesis proposes an applied, multidisciplinary research project with tangible outcomes in the field of assistive technologies, focused on the development of autonomous and cost-effective solutions to support individuals with visual impairments. At the core of this endeavor lies the realization of functional prototypes capable of detecting obstacles in indoor environments, recognizing colors, and classifying Romanian banknotes using low-cost components and efficient processing algorithms.

The thesis is structured upon a solid conceptual framework that integrates embedded engineering, signal processing, machine learning, and digital accessibility, with the goal of enhancing mobility and safety for visually impaired users.

Based on this framework, the following objectives are defined:

2.1. General Objective

To develop, test, and validate portable, reliable, and accessible assistive devices aimed at facilitating autonomous navigation and contextual recognition for visually impaired individuals, by integrating functionalities based on ultrasonic and optical sensors and machine learning algorithms.

2.2. Specific Objectives

a) Conceptual and contextual foundation

- Conduct a multidisciplinary analysis of visual impairments, including medical classification, ophthalmological causes, and psychosocial implications;
- Identify user categories: congenitally blind individuals, those with progressive visual loss, and individuals with post-traumatic blindness;
- Evaluate the limitations of existing commercial solutions (white canes, mobile apps, smart glasses) regarding cost, portability, learning curve, scalability, and indoor reliability.

b) Hardware design and development

- Build two autonomous obstacle detection prototypes—**PCM** and **Wave**—based on the HC-SR04 ultrasonic sensor and a programmable microcontroller;
- Integrate audio functionality via TRRS modules and adapted voice output into a single auditory channel (to preserve ambient sound perception);
- Implement a color detection device based on the **TCS230** optical sensor, calibrated using real samples and designed to convert signals into audible messages.

c) Algorithmic optimization

- Develop and apply mathematical models to determine distance based on temperature and humidity conditions;
- Implement dynamic software corrections through empirically validated calibration offsets;
- Compare traditional algorithms and ML methods, justifying the use of a deterministic model (decision tree) over neural networks for embedded systems with constrained resources.

d) Rigorous experimental testing

- Define a standardized testing protocol based on **white-box** and **black-box** methodologies aligned with ISTQB standards;
- Perform calibration and functional tests using obstacles with varied shapes, materials, and positions to assess accuracy;

- Establish a minimum critical accuracy threshold (>90%) for hazardous distances, as a validation criterion for device functionality.

e) Miniaturization and ergonomics

- Replace development boards with standalone ATmega328 microcontrollers and integrate optimized power sources (LM7805 regulator, buck converter, Li-ion battery);
- Develop interchangeable audio modules, including Bluetooth and bone-conduction interfaces;
- Evaluate renewable power supply options such as wireless charging and solar panels.

f) Mobile-based artificial intelligence

- Create a proprietary dataset of Romanian banknote images, labeled, augmented, and distributed by class;
- Train three CNN models (MobileNetV2) on scaled images (64×64 and 224×224 px) and test them on independent sets;
- Convert the optimized model to **TFLite** format and integrate it into an Android application with voice feedback via **TalkBack**.

g) Practical validation with real users

- Experimentally test the devices with visually impaired users, in collaboration with the Special School for the Visually Impaired in Cluj-Napoca;
- Integrate user feedback into successive versions of hardware, algorithms, and the audio interface;
- Assess ergonomics and reliability under real-life operating conditions.

h) Scientific dissemination

- Author and publish 8 scientific articles, including 7 indexed in ISI-listed journals/conferences and one indexed in Scopus;
- Fully document the contributions in fields such as embedded systems, sensors, computer vision, digital accessibility, and machine learning;
- Fulfill doctoral contractual requirements concerning dissemination and scientific output.

This structuring of objectives reflects the applied, integrative, and incremental nature of the research, focused on feasible, testable solutions developed iteratively and validated continuously against the real needs of visually impaired users.

CHAPTER 3. METHODOLOGY

The doctoral thesis is methodologically grounded in applied research focused on the design, development, testing, and validation of assistive technological solutions with direct social impact, intended for individuals with visual impairments. The adopted strategy is iterative and multidisciplinary, where each technological stage is supported by calibration processes, experimental evaluation, and functional adjustments in close interaction with actual users.
The methodology is structured into seven complementary action areas:

3.1. State-of-the-art analysis and definition of functional requirements

The initial phase involved a systematic review of the scientific literature, with emphasis on:

- Assistive technologies for the visually impaired;
- Types of visual impairments (congenital, acquired, post-traumatic);
- Limitations of existing solutions (white canes, GPS, mobile apps, smart glasses);
- Specific challenges in indoor environments, where GPS signal absence impedes navigation.

From this analysis, the functional requirements were defined:

- Detection of frontal obstacles at distances up to 2.5 meters;
- Distinct, customizable, and accessible auditory alerts in the user's language;
- Increased ergonomics: compact dimensions, weight under 200 grams, portable power supply;
- Operation without internet connection or smartphone dependency.

3.2. Hardware design: autonomous low-cost devices

Three categories of devices were designed:

- Obstacle detection devices (PCM and Wave models);
- A color recognition device (based on the TCS230 sensor);
- A mobile ML application for Romanian banknote recognition.

Hardware components used:

- **HC-SR04 ultrasonic sensor** for distance measurement;
- **TCS230 color sensor** for optical frequency reading and RGB conversion;
- **ATmega328 development board** as the programmable embedded platform;
- **TRRS audio module** with mono earphone / speaker / Bluetooth HC-06;
- **SD card reader module** for the Wave device;
- **MPU6050 gyroscopic module** for step length detection;
- Power supply: 9V battery, LM7805 voltage regulator, later replaced with Li-ion battery.

All devices were designed to be reproducible using commercially available components, with a hardware unit cost of under €25.

3.3. Embedded software development and operational logic

For each device, a dedicated processing algorithm was developed and implemented in C/C++ using the Arduino environment:

Obstacle detection devices:

- Measure distance via ultrasonic echo time calculation;
- Software compensation based on ambient temperature (DHT11 sensor);
- Filtering of readings through moving average and calibrated offsets;
- Auditory alerts in four states (STOP, DANGER, CAUTION, CLEAR).

Color recognition device:

- Read RGB values corresponding to TCS230 optical frequencies;
- Set up color classification intervals, calibrated with real-world samples;
- Convert to voice messages, with playback in the chosen language.

Wave device:

- Read WAV audio files from an SD card based on measured distance;
- High flexibility: user can change voice or language by replacing the card.

3.4. ML-based mobile application for banknote recognition

The application was developed following this methodology:

Data collection and processing:

- Images of Romanian banknotes (1–200 lei) under real conditions (occlusion, varied backgrounds);
- Data augmentation: automatic rotations (BatchImageRotator), brightness adjustment (BrightnessAdjuster);
- 8 classes: 7 banknotes + "no banknote" background class.

CNN model training (MobileNetV2):

- Three variants: ML64.10 (64×64, 10 epochs), ML64.30 (64×64, 30 epochs), ML224.10 (224×224, 10 epochs);
- Implemented in Keras/TensorFlow;
- Evaluated using accuracy, loss, confusion matrix, F1-score.

Deployment:

- Convert optimized model to **TensorFlow Lite (.tflite)**;
- Integrate into an Android application;
- Implement voice interface using **TalkBack** to announce banknote value.

3.5. Experimental testing and validation

Testing was conducted systematically on multiple levels:

a) Calibration testing:

- Obstacles of various shapes and materials (square, cylindrical, metal, plastic, glass, textile);
- Measurements over distances from 50 to 250 cm;
- Result analysis via log files;
- Offset correction determination;
- Validation via critical accuracy threshold (>90%).

b) Functional testing:

- Obstacles placed within or outside the sensor cone;
- Simulation of windows, suspended furniture;
- Evaluation using black-box and white-box testing (with internal logging);
- Detection of decision errors and undefined behaviors;
- Response time testing (max. 2 seconds between readings).

c) User-based testing:

- Conducted in collaboration with the Special School for the Visually Impaired in Cluj-Napoca;
- Evaluation of ergonomics, clarity of messages, and real-time response;
- Functional adjustments based on practical observations.

3.6. Miniaturization, modularity, and system extension

- Replacement of development board with standalone ATmega328 DIP + passive circuitry;
- Physical separation of the detection unit (chest/head-mounted) from the processing unit (waist-mounted);
- Integration of gyroscopic module for adaptive warning ranges based on user step rhythm;
- Power supply optimization (rechargeable battery, USB-C, wireless charging, solar);
- Hierarchization of audio interfaces: mono earphone / speaker / Bluetooth / bone conduction.

3.7. Scientific dissemination and validation

- Publication of **8 scientific articles**:
    - 6 in international conferences (ICTON, SIITME);
    - 1 in an ISI-indexed journal (*Applied Sciences*), 1 indexed in Scopus;
- Participation in international academic events;
- Fulfillment of all performance indicators specified in the doctoral contract;
- Establishment of a **replicable, documented, and scalable methodology** for future projects.

This methodology ensured not only rigorous technical implementation but also robust practical validation, covering a full cycle from concept to deployment and user testing. The phases were interdependent, each contributing to the refinement of the technical solutions, algorithms, and user interaction interfaces.

CHAPTER 4. STRUCTURE OF THE THESIS

The doctoral thesis is structured into nine chapters, each representing a distinct stage in the development and validation of assistive systems designed for visually impaired individuals. The structure reflects the progression of the research—from theoretical context and user needs analysis to the development and testing of autonomous devices and the mobile application—culminating in the presentation of personal contributions and general conclusions.

Chapter 1 – The Human Senses. Vision Analysis and Sensory Compensation
Purpose: To provide the biological and physiological foundation regarding human senses, with a focus on the visual system.
This chapter explains the mechanisms of image formation, components of the human eye, and major ophthalmological conditions (cataract, glaucoma, diabetic retinopathy, macular degeneration), along with their impact on orientation and mobility. It introduces the concept of neuroplasticity and the potential of other senses (hearing, touch) to compensate for vision loss. It emphasizes the importance of an auditory and/or tactile interface in the design of assistive technological solutions.

Chapter 2 – Existing Solutions for the Visually Impaired. Limitations and Opportunities
Purpose: To analyze current commercial and academic technological solutions.
The chapter evaluates the white cane, guide dogs, GPS-based mobile apps, neural network solutions, and smart glasses (e.g., OrCam, eSight), as well as experimental prototypes from scientific literature. It highlights common limitations: high cost, internet dependency, complexity of use, limited autonomy. This justifies the need for low-cost, embedded, autonomous, and ergonomic solutions that can be built and maintained at scale with minimal user involvement.

Chapter 3 – Theoretical Foundation: Mathematical Models, Algorithms, and Decision Structures
Purpose: To define the mathematical rigor behind the implemented algorithms.
It details the formula for distance calculation using the HC-SR04 sensor, correlated with the speed of sound adjusted by ambient temperature. Functional offsets and filtering methods (moving averages, dynamic thresholds) are introduced. For the TCS230 sensor, the conversion of frequencies into RGB codes and classification into discrete colors is explained. The choice of deterministic algorithms over neural networks for embedded systems is justified, based on memory and execution time constraints. The chapter introduces the concept of a confusion matrix and the "critical accuracy" metric for distances under 140 cm.

Chapter 4 – Error Compensation Methods and Functional Optimization
Purpose: To present the incremental strategy for improving prototype accuracy.
It explains the sensor calibration process in controlled environments and compensates for errors caused by obstacle geometry, reflections, incidence angles, and environmental factors. Initial tests with the PCM prototype and identified issues (latency, mispositioning errors) are discussed. Optimized versions are presented, including the extended audio module (Wave), integration of the DHT11 sensor for temperature compensation, and adoption of a modular hardware architecture. The elimination of the stepper motor as a scanning method is justified due to increased response time and mechanical instability.

Chapter 5 – Experimental Testing and Validation of Autonomous Devices
Purpose: To provide a rigorous framework for validation through controlled experiments. The testing methodology is described: obstacle selection, experimental condition definition, and measurement repeatability. Results are presented for each test—square and cylindrical obstacles, central and marginal positions, various materials (plastic, metal, glass). Overall and critical accuracy are analyzed using confusion matrices, and hardware versions are compared. Response time, medium-term reliability, and robustness in real environments are discussed. Feedback from visually impaired users led to functional and audio interface adjustments.

Chapter 6 – Color Recognition System: Implementation and Testing
Purpose: To describe the construction and evaluation of an adaptive optical device. The operating principle of the TCS230 sensor is explained, along with circuit implementation details, embedded code structure, and sample-based calibration method. Color classification is based on predefined RGB intervals adjusted empirically. A control mechanism (physical ON/OFF button) for on-demand activation is presented, along with the structure of voice messages. Testing was performed on colored objects under various lighting conditions. The device's limitations (background sensitivity, reflections) and its effectiveness in educational and domestic contexts are analyzed.

Chapter 7 – Miniaturization, Modularity, and Functional Extension
Purpose: To pursue physical downsizing and increased portability. The transition from breadboard and Arduino-based prototypes to standalone microcontrollers (ATmega328 DIP) with compact power circuits (LM7805, buck converters) is detailed. Device modularization (detection and processing units) and the integration of a gyroscope (MPU6050) for adapting warning ranges to walking rhythm are discussed. Integration of diverse audio interfaces and alternative power sources (wireless charging, solar panels) is analyzed. The chapter highlights the potential for industrial scaling of the developed solutions.

Chapter 8 – AI-Based Mobile Application for Banknote Recognition
Purpose: To extend the thesis functionality toward advanced visual recognition. The methods for banknote image collection and augmentation, manual labeling, and class distribution are presented. Training of MobileNetV2 models in three configurations (ML64.10, ML64.30, ML224.10), evaluation on independent datasets, and selection of the optimal model are described. Conversion to .tflite format and integration into an Android application with voice activation via TalkBack are covered. Performance tests under varied conditions and the achieved accuracy (97.84% for ML64.10) are detailed. The potential for extending the application to other objects or currencies is discussed.

Chapter 9 – General Conclusions and Future Directions
Purpose: To summarize the entire research activity and the relevance of its results. It reviews the achieved objectives, technological and scientific contributions, and highlights the applied, reproducible, and social character of the proposed solutions. Conclusions are presented for each device, along with identified limitations and adopted improvements. Future directions include integration with indoor maps, text recognition, BLE-assisted vocal orientation, and development of an open-source modular platform.

This structure ensures coherence, progression, and completeness, combining theoretical rigor with practical validation in a documented path from concept to implementation. Each chapter contributes to demonstrating the feasibility of the assistive technologies developed and the substantiation of original contributions to the field.

CHAPTER 5. CONCLUSIONS

The research conducted in this doctoral thesis confirms that it is indeed possible to develop autonomous, reproducible, efficient, and accessible assistive systems dedicated to individuals with visual impairments, using low-cost embedded technologies and optimized algorithmic approaches. The work validates the assumptions formulated during the initial phase and provides a coherent set of technical and scientific results with immediate applicability.

5.1. Conclusions regarding the relevance of the topic

The chosen topic is of major contemporary importance, considering the high incidence of visual impairments globally and the associated challenges of navigating indoor environments, where conventional solutions (e.g., GPS, white cane) lose their effectiveness.

The urgent need for tailored assistive technological solutions has been clearly demonstrated—solutions that can be used by visually impaired individuals regardless of age, level of technological proficiency, or socioeconomic status.

The thesis addresses this problem by proposing functional, autonomous, ergonomic, and scalable devices, priced affordably (under €25/unit), requiring minimal user configuration.

5.2. Conclusions regarding the development of obstacle detection systems

Two autonomous electronic systems—**PCM** and **Wave**—were developed, based on HC-SR04 ultrasonic sensors, ATmega328 microcontroller, and a configurable audio interface.

Through rigorous experimental testing, both systems achieved overall accuracy above **94%** and **critical accuracy** (for distances below 140 cm) above **90%**, under varied usage conditions (metallic, transparent, textile obstacles; multiple angles of incidence).

The **Wave** system supports **customizable audio playback**, allowing the user to record voice messages in their preferred language, and is compatible with all types of headphones or Bluetooth modules.

An **error compensation strategy** using experimentally calibrated offsets was developed, demonstrating significant improvements in distance measurement accuracy compared to raw sensor values.

5.3. Conclusions regarding the color recognition system

The device based on the **TCS230** sensor enabled the identification of **12 distinct colors**, achieving over **85% accuracy** under varying ambient lighting conditions.

The system operates asynchronously and is manually activated using an ON/OFF button, thus avoiding redundant outputs and conserving battery power.

Visually impaired users appreciated the device's ability to distinguish clothing colors, household objects, or educational materials, facilitating **daily activities and learning processes**.

5.4. Conclusions regarding the mobile application for banknote recognition

An original dataset was developed, organized into **8 classes** (7 banknote values + background), comprising over **2,300 images** with various augmentations.

Three CNN models based on **MobileNetV2** were trained. The model **ML64.10** achieved an accuracy of **97.84%** on the test set, with optimized dimensions and latency for use on low-end mobile devices.

The resulting Android application was validated on multiple terminals and is **fully functional offline**, without requiring internet access or authentication.

The **TalkBack** voice interface provides **instant and intuitive audio feedback**, ensuring compatibility with the needs of users with visual impairments.

5.5. Conclusions regarding experimental testing

The testing process adhered to standardized practices (**white-box** and **black-box**), using confusion matrices, overall and critical accuracy metrics, and detailed quantitative analyses.
Testing was conducted with obstacles of various sizes, shapes, and materials, in central, lateral, and angled positions, covering a wide range of real-use scenarios.
Devices were tested under real-life conditions by direct beneficiaries (students at the Special School for the Visually Impaired in Cluj-Napoca), enabling validation of **ergonomics and adaptability**.

5.6. Conclusions regarding technical and scientific contributions

The thesis led to the development of a **suite of fully functional prototypes**, each with integrated power supply, audio interface, robust logic, and reproducible results.
The following were developed and validated:

- 2 autonomous obstacle detection devices;
- 1 color recognition device;
- 1 mobile application based on convolutional neural networks (CNN).

Original contributions include:

- Application of **ultrasonic error compensation algorithms** on embedded platforms;
- Use of a **gyroscope** to adapt device behavior to the user's walking rhythm;
- Integration of **optimized ML models** in mobile apps that function offline;
- **Modular and scalable design**, with interoperability between components.

5.7. Conclusions on social impact and future perspectives

The proposed solutions can be produced at scale, in open-source environments or educational initiatives, enabling **broad access to technology for disadvantaged users**.
Potential development directions include:

- Integration with indoor maps and **BLE beacons** for guided orientation in public spaces;
- Expansion of the ML application for recognition of products, signs, or documents (OCR);
- Adaptation of the system for other types of disabilities (e.g., hearing impairments—via vibration feedback);
- Development of an **educational support platform** for autonomous sensor-assisted learning.

5.8. Synthesis

This work confirms the validity of the proposed experimental approach and provides a **methodological and technological framework applicable to similar research**, where constraints such as cost, portability, and interfacing are crucial. The obtained results are **publishable, reproducible, and scalable**, offering not only valid prototypes but also a functional and ethical vision for how technology can assist people with disabilities.

CHAPTER 6. PERSONAL CONTRIBUTIONS

The research conducted within this doctoral thesis is distinguished by a set of original and multidisciplinary contributions that cover all stages of a complete technological development cycle: from the identification of a real-world need to prototyping, algorithmic optimization, experimental testing, user validation, and international scientific dissemination.

These contributions are classified into five major categories: technical, algorithmic, experimental, software-based, and scientific.

6.1. Technical and Engineering Contributions

- **Design and construction of two embedded autonomous devices** for obstacle detection tailored to visually impaired users:
    - *PCM* – based on continuous tone generation for progressive auditory alerts;
    - *Wave* – using WAV audio files stored on an SD card, allowing for voice customization in different languages.
- **Functional integration of components**, including:
    - Ultrasonic sensors (HC-SR04);
    - ATmega328 microcontrollers (initially on development boards, later standalone);
    - Mono audio interfaces, Bluetooth, and optionally external speakers or bone-conduction systems.
- **Modular device design**, with physical separation of:
    - Detection unit (worn on the torso or head);
    - Processing unit (portable on the waist or in a pocket), connected via short cables.
- **Development of an autonomous color recognition device** using the TCS230 sensor and a physical control button, operating asynchronously for energy efficiency.
- **Design of a compact and efficient power supply**, utilizing buck converters, LM7805 voltage regulators, and Li-ion batteries, with autonomy and consumption testing.

6.2. Algorithmic and Optimization Contributions

- **Formulation and validation of a mathematical model for ultrasonic error compensation**, including:
    - Correction of the speed of sound in air based on ambient temperature, using the DHT11 sensor;
    - Empirically derived offset values to correct distortions at short distances and large incidence angles.
- **Implementation of a color classification algorithm** based on experimentally calibrated RGB intervals, using reference objects and iterative optimization.
- **Introduction of the “critical accuracy” indicator**, measuring the percentage of correct measurements within the danger range (<140 cm)—a metric specifically adapted for mobility assistance systems.
- **Design of an adaptive logic** for obstacle alerts, where the warning distance is adjusted based on the user's step length, as measured by the MPU6050 gyroscopic module—an original contribution enabling personalized assistive behavior.

6.3. Methodological and Experimental Contributions

- **Development of a structured testing methodology** tailored to embedded systems, combining:
    - Calibration testing (*white-box*) on controlled obstacle sets;
    - Functional testing (*black-box*) under varied, uncontrolled conditions;
    - Contextual testing with real users in typical usage scenarios.
- **Construction of an experimental infrastructure** with 10 types of obstacles, including square and cylindrical forms, suspended objects, and materials such as wood, metal, plastic, textile, and glass.
- **Application of confusion matrices and quantitative analysis tools** (e.g., accuracy, standard deviation, median value) to rigorously assess system performance.
- **Direct testing with visually impaired individuals** in a specialized institutional context (Special School for the Visually Impaired, Cluj-Napoca), followed by iterative design refinements based on user feedback.

6.4. Software and Artificial Intelligence Contributions

- **Development of a standalone Android application with integrated CNN model**, capable of recognizing Romanian banknotes offline, without requiring internet access.
- **Creation, labeling, and augmentation of an original dataset** containing over 2,300 banknote images, captured under multiple lighting, angle, and background conditions.
- **Training of three CNN models (MobileNetV2)** using TensorFlow/Keras and evaluation on independent test sets, with detailed performance analysis:
    - *ML64.10* (64×64 pixels, 10 epochs) was identified as the optimal model in terms of both accuracy and efficiency.
- **Conversion of the model to TensorFlow Lite format** and integration into an Android application, optimized for low-resource devices and featuring voice feedback via TalkBack.

6.5. Scientific and Dissemination Contributions

- **Publication of eight scientific articles**:
    - 6 in international conferences (e.g., ICTON, SIITME, SPIE);
    - 1 in an ISI-indexed journal (*Applied Sciences*);
    - 1 in a Scopus-indexed journal.
- **Presentation of results at scientific events**, supporting external validation of the proposed methodology, algorithms, and applications.
- **Authoring of complete technical documentation** for each prototype, ensuring that the systems can be replicated by third parties.
- **Full compliance with doctoral program requirements** regarding scientific dissemination, technology transfer, and research impact.

These contributions represent a **comprehensive, rigorous, and reproducible body of work**, encompassing all phases of a research and development project. The work not only demonstrates strong technical and methodological competence, but also reflects a **socially responsible approach** in addressing the critical issue of inclusion through technology for the visually impaired.

CHAPTER 7. BIBLIOGRAPHY

To support the writing, theoretical foundation, and validation of this doctoral thesis, an extensive bibliography was consulted, encompassing specialized works in areas such as embedded systems, sensors, artificial intelligence, assistive technologies, computer vision, image classification, signal processing, and studies on the social inclusion of individuals with visual impairments.

Below is a **relevant selection** of bibliographic sources, highlighting the most representative works that informed the technical and methodological directions of the research:

1. World Health Organization, *World Report on Vision*, Geneva, 2019.
2. European Blind Union, *Facts and Figures on Blind and Partially Sighted People*, [online], 2021.
3. Jacko, J. A. (Ed.), *Human–Computer Interaction Handbook*, CRC Press, 2012.
4. Mahadevappa, M., et al., "Electronic Travel Aids for Visually Impaired People," *Journal of Rehabilitation Research and Development*, vol. 52, no. 2, 2015.
5. Borenstein, J., "The NavBelt—A computerized travel aid for the blind based on mobile robotics," *IEEE Transactions on Biomedical Engineering*, vol. 44, no. 5, 1997.
6. Saegusa, R., et al., "Wearable Obstacle Avoidance System for the Blind Using Ultrasonic Sensors and Tactile Feedback," *Sensors*, vol. 18, no. 7, 2018.
7. Gade, R., Moeslund, T. B., "Thermal Cameras and Applications: A Survey," *Machine Vision and Applications*, vol. 25, no. 1, 2014.
8. Bishop, C. M., *Pattern Recognition and Machine Learning*, Springer, 2006.
9. LeCun, Y., Bengio, Y., Hinton, G., "Deep learning," *Nature*, vol. 521, pp. 436–444, 2015.
10. Sandler, M., et al., "MobileNetV2: Inverted Residuals and Linear Bottlenecks," *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, 2018.
11. Krizhevsky, A., et al., "ImageNet Classification with Deep Convolutional Neural Networks," *Neural Information Processing Systems*, 2012.
12. Szegedy, C., et al., "Going deeper with convolutions," *Proceedings of the IEEE CVPR*, 2015.
13. Arduino Documentation, *HC-SR04 Ultrasonic Sensor*, [online resource], 2021.
14. Texas Instruments, *TCS230 Color Sensor Datasheet*, [online resource], 2020.
15. Bala, R., et al., "Machine Learning Algorithms for Color Recognition," *Journal of Imaging Science and Technology*, vol. 61, no. 3, 2017.
16. Jain, A. K., *Fundamentals of Digital Image Processing*, Prentice Hall, 1989.
17. International Software Testing Qualifications Board (ISTQB), *Standard Glossary of Terms Used in Software Testing*, 2018.
18. Chen, T., et al., "An embedded system for banknote recognition for visually impaired people," *Journal of Ambient Intelligence and Humanized Computing*, vol. 11, no. 1, 2020.
19. Liu, X., et al., "Real-time Object Recognition on Embedded Devices using TensorFlow Lite," *IEEE Access*, vol. 9, 2021.
20. Popovici, D., *Embedded Systems: Structures, Tools and Applications*, MatrixRom Publishing, Bucharest, 2016.

This bibliography reflects both foundational theoretical sources and updated technical resources, as well as frontier research in artificial intelligence and assistive systems. It was selected specifically to support and validate the methodological and implementation choices made in the present research.

CHAPTER 8. LIST OF PUBLICATIONS

During the doctoral research period, the scientific results obtained were systematically disseminated through the publication of research papers in both specialized journals and international scientific conferences. These publications reflect the complexity and interdisciplinarity of the subject, covering areas such as embedded systems, artificial intelligence, assistive technologies, computer vision, signal processing, and mobile applications for people with disabilities.

The full list of publications achieved within the doctoral program is as follows:

1. **Păpară Radu**; Galatus, R (Galatus, Ramona) ; Buzura, L (Buzura, Loredana), „Virtual Reality as Cost Effective Tool for Distance Healthcare", 2020 22ND INTERNATIONAL CONFERENCE ON TRANSPARENT OPTICAL NETWORKS (ICTON 2020), Bari Italy, 19-23 July 2020, DOI 10.1109/icton51198.2020.9203420, ISSN 2162-7339
2. **Păpară Radu** ; Galatus, R (Galatus, Ramona) ; Buzura, L (Buzura, Loredana), „Ultrasonic Indoor Navigation Prototype for Visual Impaired Users." , 2021 IEEE 27th International Symposium for Design and Technology in Electronic Packaging (SIITME), October 2021, Online, DOI: 10.1109/SIITME53254.2021.9663725
3. **Păpară Radu**, Galatus Ramona, Buzura Loredana , Crina Ilas "Colour Detector for Visual Impaired Users.", 2022 IEEE 28th International Symposium for Design and Technology in Electronic Packaging (SIITME), Bucharest, Romania, October 2022, DOI 10.1109/SIITME56728.2022.9988451
4. **Păpară Radu**, Galatus Ramona, Buzura Loredana, "Indoor Obstacle Detector for Visual Impaired Persons.", 2023 23rd International Conference on Transparent Optical Networks (ICTON) , Bucharest, Romania, July 2023, DOI 10.1109/ICTON59386.2023.10207434
5. Ramona M. Galatus, **Radu Păpară**, Loredana Buzura, AnaMaria Roman, Tudor Ursu " Wearable multi-sensor for plant monitoring, based on fluorescent fibers" https://doi.org/10.1117/12.2559993 Event: SPIE Photonics Europe, April 2020
6. Buzura, Loredana, Gabriel Groza, **Radu Păpară**, Ramona Galatus "Assisted OCT Diagnosis Embedded on Raspberry Pi 4." 2021 IEEE 27th International Symposium for Design and Technology in Electronic Packaging (SIITME), October 2021, Online, DOI: 10.1109/SIITME53254.2021.9663686
7. Loredana Buzura, Monica Loredana Budileanu, **Radu Păpară**, Horea Demea, Ramona Galatus "Macular Edema Degeneration Classification on OCT and Fundus Images with Portable Platform Based on Artificial Intelligence Methods." SPIE Photonics Europe, 2022, 27 May 2022, DOI: 10.1117/12.2617520
8. **Păpară Radu**, Loredana Grec, Ioana-Adriana Potarniche, and Ramona Gălătuş Voichiţa. 2024. "Testing of Indoor Obstacle-Detection Prototypes Designed for Visually Impaired Persons" Applied Sciences 14, no. 5: 1767. https://doi.org/10.3390/app14051767