Bachelor Project

Czech
Technical
University
in Prague

F3

Faculty of Electrical Engineering
Department of Computer Graphics and Interaction

Method for cognitive map externalization

Iryna Parasiuk

Supervisor: Ing. Miroslav Macík, Ph.D.
Field of study: Open Informatics
Specialization: Computer Games and Graphics
May Prague 2025

BACHELOR‘S THESIS ASSIGNMENT

I. Personal and study details

Student's name: **Parasiuk Iryna** Personal ID number: **510860**

Faculty / Institute: **Faculty of Electrical Engineering**

Department / Institute: **Department of Computer Graphics and Interaction**

Study program: **Open Informatics**

Specialisation: **Computer Games and Graphics**

II. Bachelor’s thesis details

Bachelor’s thesis title in English:

Method for cognitive map externalization

Bachelor’s thesis title in Czech:

Metoda pro externalizaci kognitivních map

Name and workplace of bachelor’s thesis supervisor:

Ing. Miroslav Macík, Ph.D. Department of Computer Graphics and Interaction

Name and workplace of second bachelor’s thesis supervisor or consultant:

Date of bachelor’s thesis assignment: **03.02.2025** Deadline for bachelor thesis submission: ____________

Assignment valid until: **20.09.2026**

Head of department’s signature

prof. Mgr. Petr Páta, Ph.D.
Vice-dean´s signature on behalf of the Dean

III. Assignment receipt

The student acknowledges that the bachelor’s thesis is an individual work.
The student must produce her thesis without the assistance of others, with the exception of provided consultations.
Within the bachelor’s thesis, the author must state the names of consultants and include a list of references.

Date of assignment receipt

Student’s signature

BACHELOR‘S THESIS ASSIGNMENT

I. Personal and study details

Student's name: **Parasiuk Iryna** Personal ID number: **510860**

Faculty / Institute: **Faculty of Electrical Engineering**

Department / Institute: **Department of Computer Graphics and Interaction**

Study program: **Open Informatics**

Specialisation: **Computer Games and Graphics**

II. Bachelor’s thesis details

Bachelor’s thesis title in English:

Method for cognitive map externalization

Bachelor’s thesis title in Czech:

Metoda pro externalizaci kognitivních map

Guidelines:

Individuals with vision impairments (VI) need specific tools to acquire spatial knowledge of the environment they need to orientate in, such as building floors. Such knowledge is called a cognitive map (CM) of the spatial environment. Several methods exist to provide spatial knowledge to VI, ranging from verbal descriptions through interactive tactile maps to virtual reality. The measurements of CM quality require specific strategies, including CM externalization. In the case of VI, the CM externalization methods must be maximally accessible to be efficient and allow CM evaluation with adequate precision.
Analyze available methods for the evaluation of spatial cognitive maps (CM), focusing on strategies based on CM externalization. Include the following sources in your analysis [1-3]. Analyze the target user audience of individuals with vision impairments, focusing on their needs, preferences, and requirements related to CM and CM evaluation methods.
Familiarize yourself with the project Haptic Tiles (interactive tactile maps of rooms for individuals with vision impairments) [4,5]. Analyze suitable computer vision (CV) methods for tracking objects (object type, position, orientation). Methods requiring tracker codes are acceptable. Conclude the analysis by summarizing the advantages and disadvantages of these methods and by stating the functional and non-functional requirements for a new CM externalization method. Design a CM externalization method for VI and a corresponding supporting SW/HW tool. Consider incorporating multimodal interactivity into the CM externalization process. Implement a solution to demonstrate the method based on the results of the Haptic Tiles project. Evaluate the practical results with at least five representatives of the target user audience.

Bibliography / sources:

[1] Miao, M., Zeng, L., & Weber, G. (2017). Externalizing cognitive maps via map reconstruction and verbal description. Universal Access in the Information Society, 16, 667-680.
[2] Guerreiro, J., Sato, D., Ahmetovic, D., Ohn-Bar, E., Kitani, K. M., & Asakawa, C. (2020). Virtual navigation for blind people: Transferring route knowledge to the real-World. International Journal of Human-Computer Studies, 135, 102369.
[3] Ungar, S. (2018). Cognitive mapping without visual experience. In Cognitive Mapping (pp. 221-248). Routledge.
[4] Macik, M., Ivanic, T., & Treml, L. (2021). Interactive modular tactile maps of rooms for older adults with vision impairments. In Human-Computer Interaction–INTERACT 2021: 18th IFIP TC 13 International Conference, Bari, Italy, August 30–September 3, 2021, Proceedings, Part I 18 (pp. 321-330). Springer International Publishing.

[5] Macík, M., & Branig, M. (2023, August). Mid-air Haptic Cursor for Physical Objects. In IFIP Conference on Human-Computer Interaction (pp. 563-572). Cham: Springer Nature Switzerland.

FAKULTA ELEKTROTECHNICKÁ
FACULTY OF ELECTRICAL ENGINEERING
Technická 2
166 27 Praha 6

DECLARATION

I, the undersigned

Student's surname, given name(s): Parasiuk Iryna
Personal number: 510860
Programme name: Open Informatics

declare that I have elaborated the bachelor's thesis entitled

Method for cognitive map externalization

independently, and have cited all information sources used in accordance with the Methodological Instruction on the Observance of Ethical Principles in the Preparation of University Theses and with the Framework Rules for the Use of Artificial Intelligence at CTU for Academic and Pedagogical Purposes in Bachelor's and Continuing Master's Programmes.

I declare that I used artificial intelligence tools during the preparation and writing of this thesis. I verified the generated content. I hereby confirm that I am aware of the fact that I am fully responsible for the contents of the thesis.

In Prague on 14.05.2025

Iryna Parasiuk
....
student's signature

Acknowledgements

First, I would like to thank my supervisor, Ing. Miroslav Macík, Ph.D., for his consistent guidance, valuable feedback, and support throughout the development of this project.

I am also deeply grateful to my loved ones for their support, patience, and understanding, which kept me motivated and focused throughout this process.

Lastly, I would like to thank the Czech Technical University in Prague for offering the facilities and a supportive environment that helped me successfully complete this project.

Abstract

Cognitive maps are widely used in society to organize and structure knowledge about the world. These maps are particularly important for individuals with visual impairments, as these people often rely on maps to enhance their spatial orientation. Accuracy of these maps are verified through externalization methods such drawing maps on a paper, providing voice descriptions, reconstructing maps using auxiliary tools etc. These techniques help identify the errors and difficulties encountered by individuals during the creation of their mental maps. Understanding these issues and subsequently improving mental maps can significantly help people with visual impairments manage everyday tasks more easily, which supports better orientation in daily situations and increases their level of independence.

Despite the wide range of externalization methods, most of them focus on evaluating the accuracy of mental maps without actively assisting users during the testing process. This research introduces an approach that evaluates the mental map and also aids in the externalization process itself. The proposed method integrates spatial reconstruction using the interactive modular tactile maps system with voice guidance. This interactive system enables real-time feedback, helping users understand the mistakes and immediately correct them during reconstruction. Evaluation with four representatives of the target user audience indicated that the proposed solution improves CM externalization.

Keywords: cognitive map, mental map, blind people, visual impairments, externalization methods, interactive modular tactile maps system

Supervisor: Ing. Miroslav Macík, Ph.D.

Abstrakt

Kognitivní mapy jsou široce využívány ve společnosti k organizaci a strukturování znalostí o světě. Tyto mapy jsou obzvláště důležité pro osoby se zrakovým postižením, protože se na ně často spoléhají při orientaci v prostoru. Přesnost těchto map se ověřuje pomocí externalizačních metod, jako je například kreslení map na papír, hlasový popis, rekonstrukce prostoru pomocí pomocných nástrojů apod. Tyto techniky pomáhají identifikovat chyby a problémy, se kterými se setkali lidí při vytváření svých mentálních map. Porozumění těmto problémům a následné zlepšení mentální mapy může osobám se zrakovým postižením významně usnadnit zvládání každodenních činností, což přispívá k lepší orientaci v běžných situacích a zvyšuje jejich míru nezávislosti.

Navzdory širokému spektru externalizačních metod se většina z nich zaměřuje na hodnocení přesnosti mentálních map, aniž by aktivně pomáhala uživatelům během testovacího procesu. Tento výzkum představuje přístup, který hodnotí mentální mapy a zároveň napomáhá samotnému procesu externalizace. Navrhovaná metoda integruje prostorovou rekonstrukci pomocí systému Interaktivní modulární hmatové mapy s hlasovým vedením. Tento interaktivní systém umožňuje zpětnou vazbu v reálném čase, což uživatelům pomáhá pochopit své chyby a opravit je hned během rekonstrukce. Testování provedené se čtyřmi zástupci cílové uživatelské skupiny ukázalo, že navržené řešení vedlo ke zlepšení externalizace kognitivních map.

Klíčová slova: kognitivní mapa, mentální mapa, nevidomí lidé, zrakové postižení, externalizační metody, interaktivní modulární hmatové mapy

Překlad názvu: Metoda pro externalizaci kognitivních map

Contents

Figures

Tables

List of Abbreviations

VI visual impairments

VD voice description

CM cognitive maps

EM externalization methods

RM spatial reconstruction using magnetic cubes

PAM pin array matrix

Chapter 1
Introduction

The following chapter introduces the motivation for this project and provides an overview of its main goals.

1.1 Motivation

Understanding and navigating physical spaces is a critical skill for people with visual impairments (VI), as it directly impacts their independence and quality of life [2]. An important aspect of independent spatial orientation is the development of CM. According to Majerova [3], creating these mental representations of space is a complex process. As a result, some people may find it challenging, especially in unfamiliar environments. Errors in these maps often lead to disorientation, misjudgment of distances, and difficulties in navigation, which can hinder daily activities and overall confidence.

Existing externalization methods (EM), such as tactile maps [1], verbal descriptions [4], and reconstruction methods [4, 5] (e.g., spatial reconstruction using magnetic cubes (RM)), provide valuable means to assess the accuracy of CM. However, these methods typically lack real-time interactivity or offer only limited interaction during externalization, reducing the ability of users to learn and correct mistakes as they occur. For example, reconstruction methods [1, 4] may only inform users whether an object was placed correctly or incorrectly, without offering more detailed guidance to support ongoing learning. To address these limitations, this research introduces an interactive system that not only evaluates CM, but also facilitates real-time feedback through a combination of tactile exploration and auditory support. By enabling immediate guidance during the externalization process, the system aims to help individuals with VI construct more accurate spatial representations, enhancing their navigation skills and independence.

1.2 Goals

The primary goal of this project is to develop a system that facilitates the externalization of CM and supports users (individuals with VI) in enhancing their mental representations, thereby improving their spatial understanding.

In addition to the primary goal, the project addresses several supporting objectives. First, it focuses on understanding the user needs and their requirements related to the CM and CM evaluation methods. It also explores existing EM. Based on these findings, a prototype system will be designed and implemented. Finally, the solution will be evaluated with users to assess its effectiveness and usability.

In summary, the main objectives of the project are:

1. Explore methods and technologies for the externalization of CM.
2. Analyze the needs and requirements of the target user groups:
   a. *People with VI.*
   b. *Assistants of people with VI* (e.g., educators, therapists).
3. Define system functional and non-functional requirements.
4. Design and develop a method for externalizing CM with a supporting software/hardware tool.
5. Implement a prototype.
6. Evaluate the prototype with users.

After the project motivation is clarified and the main goals are defined, it is important to understand the key concepts of this work. The next chapter examines relevant theory, ideas, and background necessary for the project.

Chapter 2
Analysis

This chapter first explores the needs of individuals with VI and their assistants. Next, it defines (CM) and discusses their applications for visually impaired users. Finally, it reviews various EM and compares them.

2.1 Target User Audience

This application is designed to address the needs of two target groups: individuals with VI and those who support them, such as educators, therapists, and family members.

- **Individuals with VI**

  The primary users of this project are individuals with VI. According to Knauer et al.[6], around 90% of the sensory input is processed through vision. As a result, navigating and understanding unfamiliar environments is much more difficult for visually impaired people [7, 2, 8]. They often rely on their remaining senses and environmental cues to compensate for the lack of visual input [3, 9]. The following points highlight the needs of visually impaired people for effective spatial orientation:

  1. **Access to recognizable landmarks**
     Landmarks are noticeable elements that help people understand their location, such as physical objects (e.g., furniture, carpets), sounds (e.g., a radio, television) or smells (e.g., food, flowers).
  2. **Clear and consistent auditory cues**
     Sounds such as guiding hints, verbal instructions, or ambient noises (e.g., television, traffic or fountain) provide orientation and directional information.
  3. **Tactile feedback**
     Textures, raised surfaces, and physical markers (e.g., tactile paving, haptic maps) support spatial awareness and safe movement.

4. **Structured spatial information**
   Information about the layout should be logically organized and presented in accessible formats, such as interactive tactile maps and audio descriptions. These methods help build CM and easily remember spatial details.

- **Assistants (e.g., educators, therapists)**

  The secondary users include individuals who interact closely with visually impaired persons, such as family members, personal assistants, educators, and therapists. The following points summarize the needs of secondary users to help them provide effective assistance to visually impaired people [10, 11]:

1. **Tools with an intuitive interface**
   The system should be easy to use and facilitate effective guidance and assistance.
2. **Clear visualization of spatial layouts (space twin)**
   Visual representations help secondary users orient themselves and effectively assist, guide, and verify the primary user's understanding of the space.
3. **Tracking the progress of the visually impaired user**
   Features that allow secondary users to monitor the primary user's progress are valuable for adapting support strategies.
4. **Externalization of the visually impaired user's CM**
   The system should allow secondary user to understand how the primary user imagines the space.
5. **Correcting the visually impaired user's CM**
   The application should provide feedback and guidance to correct errors and enhance the visually impaired user's spatial understanding.

2.2 Related Work

After the user needs have been clarified, the next section covers the basic theory of CM and their externalization.

2.2.1 Cognitive Maps

Cognitive maps (CM), also known as mental maps, are widely studied and applied across various fields [12, 13, 14, 15]. Before exploring their role in this project, it is important to first define the cognitive mapping process and then explain what CM are.

According to the Kitchin study [14]:

"Cognitive mapping is a psychological process that involves a sequence of mental transformations that allow individuals to acquire, store, retrieve, and interpret information about the relative locations and characteristics of phenomena in their spatial environment." [14]

In addition, Kitchin [14] noted that CM have a wide range of definitions, which depend on the field and the way they are used. For this work, we use Tolman's definition [16]:

"A cognitive map is a type of mental representation used by an individual to order their personal store of information about their everyday or metaphorical spatial environment, and the relationship of its component parts." [16]

CM function by organizing sensory inputs and linking them with prior knowledge to create a clear representation of spatial relationships. For example, when navigating a new city, an individual combines visual landmarks, the layout of streets, and cardinal directions to form a mental representation of the area. It demonstrates that CM are not only tools for spatial navigation, but also structures for organizing various types of knowledge [14, 16].

The importance of CM is especially evident for individuals with VI, as they rely heavily on these maps during navigation.

2.2.2 The Role of Cognitive Maps for Individuals with Visual Impairments

For visually impaired people, CM are essential tools for navigation and orientation. Individuals with VI rely on a combination of *sensory inputs* (hearing, touch, smell, and taste) with *cognitive processes* (memory, attention, thinking, and imagination) to create mental representations of space [3]. Then they apply this knowledge in their daily lives to navigate and interact with the environment.

To improve their CM and orientation skills, individuals with VI can adopt various strategies and tools, including:

- **Relying on guide dogs.**
- **Using verbal descriptions.**
- **Utilizing white canes.**
- **Using mobile applications.**
- **Using variety of other assistive devices, methods and their combinations.**

However, research by Quinones et al. [7] has shown that despite having this knowledge and assistive tools, people with VI still face difficulties in navigation due to the following factors:

- **Environmental conditions** (e.g., weather).
- **Obstacles** (e.g., construction or obstructions).
- **The loss of cues** (e.g., landmarks or other navigational aids).

As a result, CM can be inaccurate and contain errors that make it difficult for individuals to perform routine activities such as traveling, navigating the right path and fulfilling basic daily needs. To solve this problem, cognitive map EM are employed.

2.2.3 Externalization Methods

Externalization methods (EM) of CM are a set of techniques that translate CM into accessible and clear formats, such as tactile and haptic representations, 3D models, and voice description (VD). These methods aim to bridge the gap between abstract spatial concepts stored in the mind and their practical application in real-world navigation and problem-solving.

Kitchin and Jacobson [17, 4] divided the cognitive map EM into the following two categories:

1. **Route-based techniques:**
   - **Retracing or inferring a route**
     Studying individuals' ability to retrace a route from the destination to the origin and their interaction with the environment.
   - **Estimating the distance**
     Determining the distance between two points of a route, which helps understand how individuals with VI perceive spatial distances.
   - **Estimating the direction**
     Determining the relative direction between the start and end points or key locations along the route, which helps to evaluate how individuals with VI perceive spatial orientation.
2. **Configurational techniques:**
   - **Graphic tests**
     All forms of sketch mapping, including freehand drawing, guided drawing tasks such as filling in parts of a map, help to determine how people with VI understand spatial relationships.

- **Partially graphic:**
  Methods based on filling in the blanks.
  - *Spatial cued response methodologies*
    Location testers involve placing points on a map based on depicted reference landmarks, such as dots or landmarks.
  - *Cloze procedure test*
    The test asks respondents to fill in missing landmarks on a gridded map or to complete sentences with blanks.
- **Reconstruction tests**
  Building a model of an environment using a modeling kit (e.g., LEGO, magnetic cubes).
- **Uni-to-multidimensional tests**
  Respondents judge distances between places, and this information is used to create a 2D map of spatial relationships.
- **Recognition tests**
  These methods present maps, photos, or tactile layouts to respondents with VI, who then identify the correct features or spatial arrangements.

The methods described in the work of Kitchin and Jacobson [17] continue to be widely used because they provide essential strategies for representing CM in an external format. Their adaptability ensures their relevance in various applications and for various groups, including individuals with VI. Building on this strong foundation, researchers [4, 8, 5, 18, 19, 1, 20] have introduced and tested advanced techniques to further enhance the externalization of CM.

For example, Miao et al. [4] compared two externalizing methods:

- **Spatial reconstruction using magnetic cubes RM.**
- **Voice description VD.**

They studied the ability of individuals with VI to externalize learned maps on *swell paper*, *an iPad with audio-proprioceptive feedback*, and *a HyperBraille device* using VD and RM. The study showed that RM produced more accurate route knowledge but was more time-consuming, while VD was less precise and more difficult to objectively assess. Participants with VI struggled with audio-proprioceptive maps. Also participants found RM easier and more accurate than VD. The authors suggest combining structured VD with gestures to improve VD method.

Luca Brayda et al.[5] investigated how individuals with VI and low vision participants, comparing three information modes to display maps: *with a pin array matrix (PAM)*, *with raised paper*, and *with VD*. To evaluate externalization of the CM, they used physical reconstruction with LEGO bricks and route-based techniques. They found that the reconstruction method was more effective than with raised paper. VD was found to be less effective, a conclusion that aligns with the findings of Papadopoulos [20] who also compared RM and VD EM.

Guerreiro et al. [8] conducted research with visually impaired individuals to investigate the acquisition route knowledge using virtual navigation. Externalization was assessed through verbal route descriptions and real-world navigation tasks (with and without mobile application named *NavCog* assistance). Most of the participants successfully transferred their virtual learning to real-world navigation, particularly for short routes.

Ottink et al. [18] in their study they worked with people with VI and sighted persons. They used an interactive tactile maps to learn the map and externalize it. These maps provided feedback (whether the participant was correct or not). The participants then performed several spatial tasks:

1. **Learning task:**
   - **Navigation task**
     Task was for participants to learn the layout of the tactile map and the item locations by navigating from item to item.
2. **Externalization tasks:**
   - **Distance estimation task**
     Participants estimated relative Euclidean and path distances between item pairs on a scale from 0 to 100.
   - **Pointing task**
     Participants pointed in the direction of item locations from a specific point on the map, assessing their directional accuracy.
   - **Route rebuilding task**
     Participants reconstructed routes between item pairs using LEGO bricks, evaluating their understanding of the layout and distances.
   - **Item placement task**
     Participants placed items on a tactile map without location markings, testing their recall and spatial memory.

Results showed no significant performance differences between the groups. Both were able to construct accurate CM and acquire survey knowledge when provided with equal access to spatial information. This supports the use of tactile maps as an effective method for externalizing and developing spatial knowledge in visually impaired individuals.

Macík et al. [1] investigated an interactive modular tactile maps of rooms, which are designed to help people acquire spatial knowledge of rooms layouts and their interior. These tactile maps use a block-based system that allows users to recreate a physical copy of a room. Additionally, RGB LEDs and buttons are integrated into each module, and the design enables detection of any push-button press in any hole of any module in the chain.

Macík et al. [19] studied mid-air tactile stimuli from ultrasonic arrays combined with an interactive haptic maps [1] as a potential method for externalizing CM. The system guides users' hands toward physical objects, aiding orientation. Their research revealed that effectiveness depends on conditions that ensure accurate tactile feedback perception, as well as on the participants' tactile sensitivity and haptic perception abilities.

Together these approaches will form the basis for a comparative analysis presented in the next subsection.

2.2.4 Comparison of Externalization Methods

All the EM discussed earlier are presented in Table 2.1 and compared based on the needs of the target users of the project (people with VI and their assistants). The symbols below indicate how effectively each method addresses a specific need:

- A plus sign (+) means the method supports this need.
- A plus-minus sign (±) means the method partially supports this need or support depends on implementation.
- A minus sign (−) means the method does not support this need.

The following summary analyzes the data presented in Table 2.1, highlighting the advantages and disadvantages of the methods for CM externalizing described above, as well as their relevance to the objectives of the project.

The first method considered is graphic tests [17, 4]. These are primarily useful for assistants, as they provide a visual representation of space (e.g., a printed map) and enable manual visual tracking of spatial understanding, as well as correction of CM (e.g., verbally). However, due to their visual nature, they are inaccessible to users with complete vision loss. Moreover, they do not provide tactile or auditory support.

Spatial reconstruction kits [4], such as LEGO, offer structured spatial information and a tactile feedback. These tools externalize a user's cognitive map in a physically manipulable format, though their effectiveness depends on the kit's design and often requires manual tracking and CM correction (e.g., through verbal or other means).

Route-based techniques [17, 8], including those supported by assistive navigation tools (e.g., NavCog) [8], align well with how users with VI experience and structure space. They support landmark recognition and internal spatial structuring, but offer limited CM correction and auditory cues unless aided by technology or an assistant (e.g., through verbal descriptions).

Verbal descriptions and questionnaires [4, 17] provide accessible means for users to articulate spatial knowledge. These methods support auditory processing and structured thinking, but may lack tactile or visual grounding. As a result, their effectiveness in tracking progress or correcting CM can be limited without the use of external tools.

Table 2.1: Comparative analysis of cognitive map EM

Externalization method	Needs of people with visual impairments				Needs of Assistants (e.g., Educators, Therapists, Family members)				
	Tactile Feedback	Auditory cues	Recognizable landmarks	Structured spatial information	Space visualization (space twin)	Tracking the progress	Intuitive interface	CM externalization	CM Correction
Graphic tests	-	-	± (Depends on visual accessibility)	± (Depends on visual accessibility)	+	± (Manually)	-	± (Depends on visual accessibility)	± (Manually)
Spatial reconstruction with different kits (e.g., LEGO)	+	-	-	+	± (Depends on kit design)	± (Manually)	-	+	± (Manually)
Route-based	-	± (Manually)	+	+	-	± (Needs external tools)	-	+	± (Manually)
Route-based with navigation tools (e.g., NavCog)	± (Depends on tool design)	± (Depends on tool design)	+	+	± (Depends on tool design)	± (Depends on tool design)	± (Depends on tool design)	+	± (Depends on tool design)
Verbal description	-	± (Manually)	-	± (Manually)	-	± (Manually)	-	+	± (Manually)
Questionary (Questions about spatial relationships)	-	± (Depends on questions)	-	± (Manually)	-	± (Manually)	-	+	± (Manually)
Interactive tactile maps	+	± (Depends on map design)	+	+	+	± (Depends on map design)	± (Depends on map design)	+	± (Depends on map design)

The last method is interactive tactile maps [1, 18]. They combine tactile and auditory feedback, offering dynamic and accessible spatial representations. These tools support externalization and correction of CM, as well as manual user progress monitoring, although they often require specialized technology.

As shown in Table 2.1, interactive tactile maps [1, 18] provide the most comprehensive support across the evaluated criteria. The following subsection summarizes and justifies the methodology selected to achieve the project objectives.

2.2.5 Analysis summary

After analyzing and comparing various EM [4, 8, 5, 18, 19, 1, 20], the methodology based on interactive tactile maps was identified as the most suitable approach. Among the different types of interactive tactile maps [1, 18], the maps developed by Macík et al. [1] were selected due to their flexibility in practical applications and their potential to address the needs of all users (people with VI and their assistants), as described previously. These maps are illustrated in Figure 2.1.

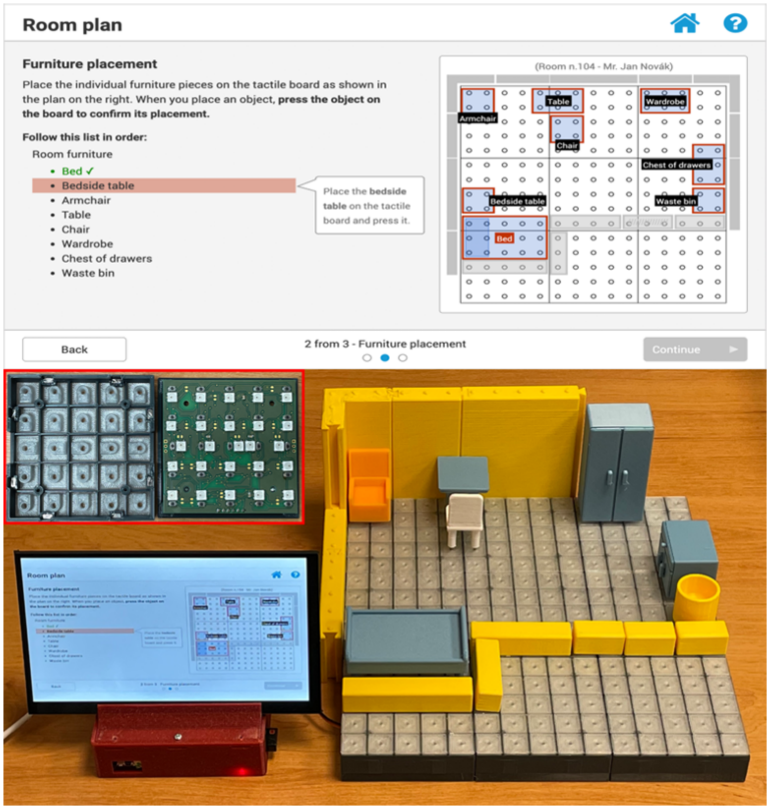

Figure 2.1: Interactive Modular Tactile Maps, from [1]

The advantages and disadvantages of this method are described below.

- **Advantages**

  1. **Provide tactile feedback and include recognizable landmarks**
     For example furniture objects, which are key components of structured spatial information.
  2. **Enable space visualization**
     This methodology includes a spatial visualization component in the form of an online application designed for secondary users (e.g., ssistants or educators), who can utilize it to interpret the spatial environment.
  3. **Includes an application with an intuitive interface**
     The interface is accessible even for users with limited technical experience, because it requires minimal time to learn how to use it.
  4. **Facilitate externalization of CM**
     These maps help externalize the CM of a person with VI in a simple way by arranging objects on a surface.
  5. **Enables the development of CM**
     This methodology offers functionality for individuals with VI to study spatial environments and develop CM.
  6. **Supports a wide range of functionalities**
     The maps are formed by modules (9 modules, each consisting of 25 cells arranged in a 5x5 grid). Each module is equipped with RGB LEDs, which enable interaction with partially sighted individuals, as well as 25 push-buttons per module, allow for more interaction capabilities.

- **Disadvantages**

  1. **Absence of cognitive map modification capabilities**
  2. **Lack of audio feedback**
     The maps currently either do not provide audio feedback or offer only minimal auditory interaction.
  3. **Absence functionality for automatic tracking of user progress**

Despite these limitations, the system demonstrates considerable flexibility and functionality. As demonstrated in the research of midair tactile stimuli based on interactive haptic maps [19], its modular architecture allows for various improvements. As a result, in our case, it becomes possible to incorporate progress tracking, cognitive map correction, and advanced audio feedback to fulfill the main objectives of the project. These potential improvements could significantly increase the effectiveness and user experience of the system.

After selecting the foundation for the project, we will now proceed to the next chapter which focuses on the project specifications and design.

Chapter 3

Design

This chapter begins with an outline of the core requirements of the project, based on the needs of the target user groups. Next, use-case scenarios are examined to illustrate the contexts and ways in which the proposed system will be utilized. Finally, the chapter proceeds to the system design and details of the software implementation process.

3.1 Requirements

To fully understand the main aspects of the project, it is first necessary to define the Functional and Non-Functional Requirements of the system.

3.1.1 Functional

1. **Interaction with tactile modules**

   The system shall provide a tactile maps with clear, easily distinguishable textures and modular components for easy interaction and exploration. It shall also support the presentation of structured spatial information.

2. **Recognition of Landmarks**

   The application shall recognize objects and provide relevant information to the user.

3. **Give audio feedback**

   The system shall deliver clear, consistent auditory cues in real-time to assist users in orientation and to guide correction of object placement on the map.

4. **Progress Tracking**

   The system shall save user data to enable analysis and monitoring of skill development over time.

5. **Intuitive Interface**

   The interface shall be simple and accessible to users.

6. **Externalization and Correction of CM**

   The system shall facilitate the externalization of users' CM in tactile and audio forms, and support their correction based on feedback.

3.1.2 Non-functional

1. **Accessibility**

   Support tactile and audio interfaces to ensure comfortable interaction for users with varying degrees of visual impairment.

2. **Real-Time Performance**

   Fast data processing (e.g., camera input, speech synthesis) to provide immediate feedback.

3. **Compatibility**

   Support for various haptic devices, cameras, and marker recognition technologies.

4. **Usability**

   Intuitive system for users that minimizes the need for extensive training.

5. **Maintainability**

   The architecture should allow straightforward updates and improvements, including the integration of new features.

After defining the key project requirements, it is now important to consider how the system may be applied in real world contexts. The subsequent section focuses on illustrating these potential scenarios.

3.2 Scenarios

Before describing the usage scenarios, it is important to note that the main focus of this project is methods for the externalization of CM. However, due to the flexibility of tactile maps [19], we also consider a scenario in which these maps are used in earlier stages of spatial cognition, such as learning, exploration, and CM formation.

Accordingly, the two scenarios are presented in logical order: the first focuses on CM formation in an unfamiliar space, and the second on CM externalization.

1. **Scenario: Learning and formation of a CM:**

   First, an assistant introduces the user with VI to tactile maps [1] representing an unfamiliar real-world space (e.g., flat or hospital room). Then, the user with VI explores this maps by touching the objects to receive auditory feedback, which includes information about this object (e.g., "A stable chair next to a table") as shown in Figure 3.1.

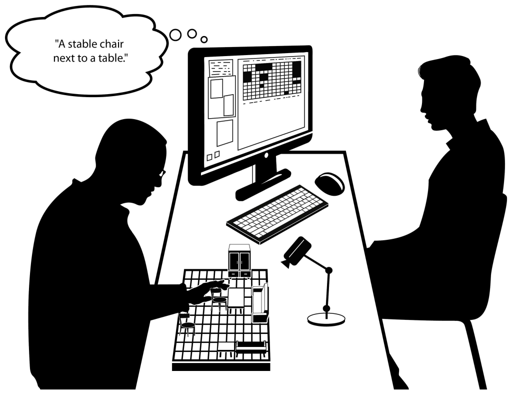

Figure 3.1: Map exploration

Through this multimodal interaction, the user builds a CM of the unfamiliar space. This prior experience helps the user navigate the real environment more effectively, enhancing their sense of autonomy and confidence (see Figure 3.2).

Figure 3.2: Navigation in a real room

After the cognitive map has been created, it is important to verify its accuracy and correctness through externalization.

2. **Scenario: Externalization of CM:**

   First, the assistant creates a virtual representation of a familiar space (e.g., an office or a room in the user's home) in order to assess the cognitive map formed by the individual with VI (see Figure 3.3).

Figure 3.3: Creation of a virtual representation of a room

Afterward, the user with VI receives tactile maps with furniture objects (identical to the virtual representation) and explores these maps and the objects.

Following exploration, the user's task is to place the furniture objects on the map according to their placement in real life (see Figure 3.4). During this process, the system provides audio guidance:

- *Specifies which object should be placed.*
- *Confirms correct placement.*
- *Offers feedback requiring object repositioning or rotation.*

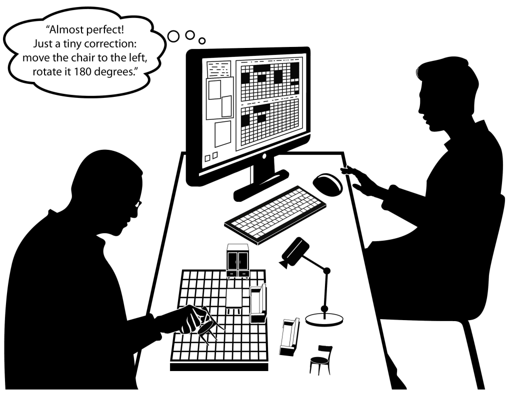

Figure 3.4: Placing furniture on the board, checking and correcting the placement

During the CM externalization an assistant can monitor the digital reconstruction, seeing the correct layout of the objects and the user's current progress. The system also tracks and records the number of errors made during object placement, generating a dataset for further analysis (see Figure 3.5).

Figure 3.5: Results and discussion

Once the externalization is complete (all the furniture objects is placed), the user is expected to have a more accurate cognitive map, which may enhance user's spatial confidence and independence in the actual environment (see Figure 3.6).

Figure 3.6: Improved CM

After the main scenarios have been described, the next step is to focus on the design and implementation of the system.

3.3 UI Design

This project builds on an updated version of the tactile map application developed by Macík et al., as originally (see Figure 2.1) introduced in [1]. This version of application also supports interaction with physical maps via a serial connection (see Figure 2.1 and Figure 3.7).

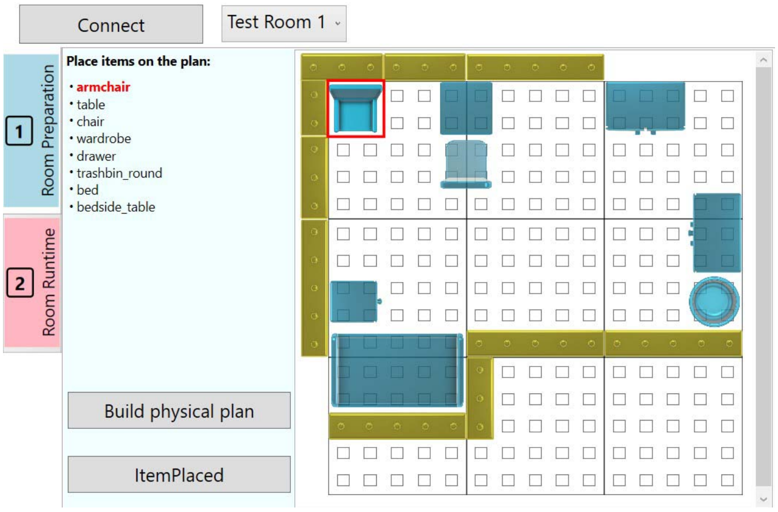

Figure 3.7: Application for the tactile maps created by Macík et al., from [1]

This version of application included two main modes:

1. **Room Preparation:**
   It can be used by assistants to arrange physical objects on the map according to a predefined layout (shown in Figure 3.7) or the people with VI as simple externalization method.
2. **Room Runtime:**
   In this mode a user with VI could explore the setup and receive auditory feedback about the objects on the tactile map upon pressing them.

While these modes enabled guided object placement and basic tactile exploration with auditory feedback, they only allowed for minimal externalization of the user's CM and did not provide any means of assessing its accuracy.

To address this limitation, the application was extended with a new module Room Comparison accessible from the updated main menu, as shown in Figure 3.8.

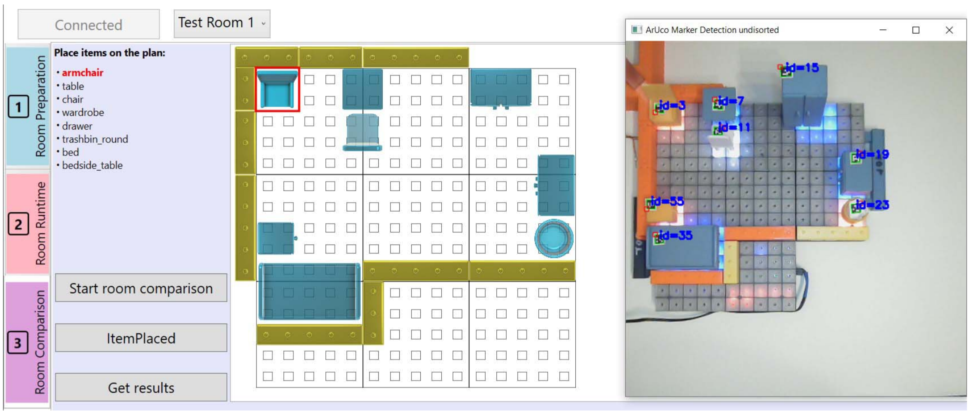

Figure 3.8: A new Room Comparison module

The project was also extended with a camera on a stand and a ring light for illumination, as shown in Figure 3.9.

Figure 3.9: Final system

The newly implemented Room Comparison mode supports the evaluation of an internally formed CM by comparing the user's object placements with the expected layout. It consists of:

1. **A Start Room Comparison button**

   It initiate the evaluation process.

2. **An Item Placed button**

   It confirms the placement of the current object. (The implementation of this function was inherited from the original application's Room Preparation mode shown in Figure 3.7.)

3. **A Get Results button**

   It saves evaluation data (detected mismatches in placement).

Concluding the UI design section, only minor changes were made to the original user interface, as the initial application was already sufficiently simple and user-friendly, requiring no significant adjustments to support the goals of this project. The newly implemented module integrates camera input and spatial detection of furniture objects, enabling real-time audio feedback about correctness of object placement, supporting the more complex externalization scenario. These aspects will be discussed in more detail in the following sections.

3.4 SW Design

The system is implemented as a multi-project Visual Studio solution using the MVVM architectural pattern. It extends the existing HapticTiles application created by Macík et al. [1] and adds a new module for real-time object placement evaluation based on object (marker) detection. The application consists of four main projects:

1. **HapticTiles**

   It is the core application implemmented by Macík et al., as shown in Figure 3.10. Building upon the existing base, two classes were added:

   a. A user control (RoomComparisonUC) provides the UI for the externalization scenario with real-time audio feedback.

   b. Its corresponding ViewModel (RoomComparisonViewModel) contains the core logic of this user control.

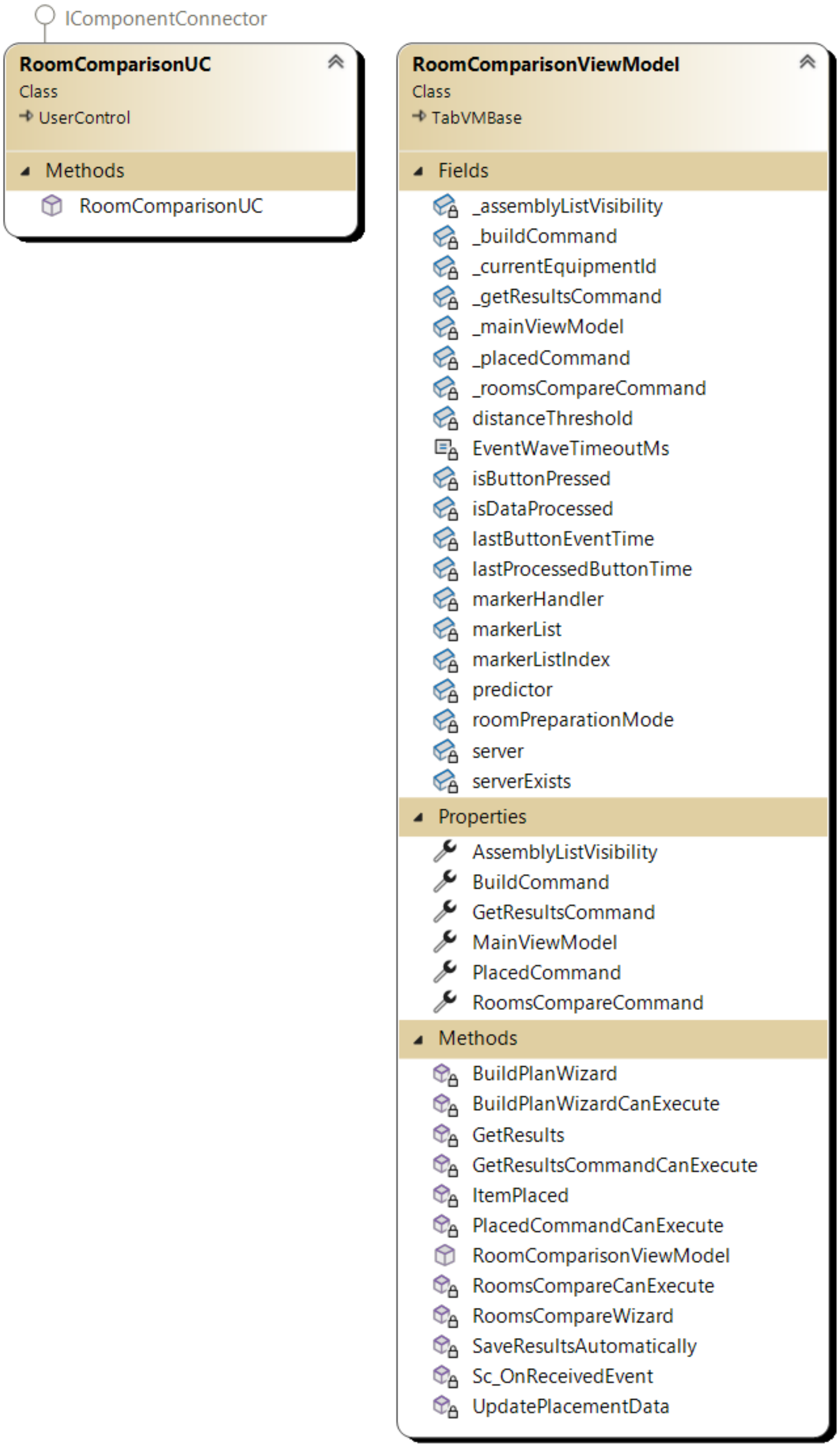

Figure 3.10: Classes added to the core HapticTiles application

2. **ArucoDetection**

   It is a console application responsible for camera input, marker detection, and transmission of marker data to the main HapticTiles application.

3. **ArucoHelpers**

   This project contains support library classes for marker management, data transmission through the TCP server (TCPClient, TCPServer), marker data storage (MarkerData, FurnitureArucoList), position validation (MarkerHandler), and marker position prediction (PredictArucoPosition) (see Figure 3.11).

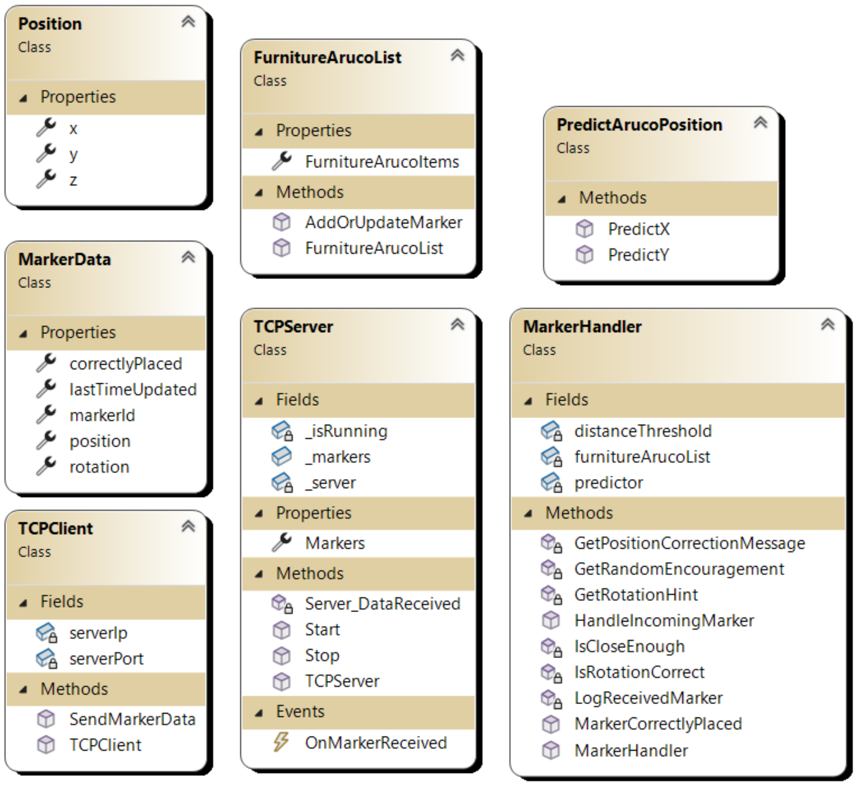

Figure 3.11: ArucoHelpers library classes

4. **GetTrainingData**

   It is a helper application created to collect and save data for machine learning model training.

To summarize, the software design introduced a new components for supporting real-time feedback during the map externalization process. This extension enables the application to assist visually impaired users more effectively by providing immediate audio guidance based on the position of physical objects. Now, we will move on to a more detailed explanation of the techniques used in the programming and implementation of the application.

Chapter 4

Implementation

This section gives a more detailed look at the techniques used to implement the main functionality of the application.

4.1 Development Tools/Methods

This section presents the main development tasks required to implement the application's functionality. Each subsection represents a specific task that was addressed to achieve the overall goal of the project.

4.1.1 Camera Integration and Object Recognition

For the recognition of objects (furniture) and interaction with the camera, the *OpenCV* library was utilized. OpenCV [21] is an open-source computer vision and machine learning software library that provides tools for real-time image processing.

Possible fiducial markers for interaction with objects were studied [22]. Among all the described markers, *Aruco* markers (4x4_1000) were selected as the most suitable.

Aruco markers are square-shaped fiducial markers that contain encoded information, which can be recognized by a camera [22]. These markers are commonly used for camera calibration, 3D object tracking, and localization. Detecting these markers, the system will accurately identify and interact with furniture pieces, assisting individuals with VI.

4.1.2 Testing the Aruco markers

Before actual development of the application, Aruco markers were tested (see Figure 4.1) to achieve better detection results. Three different sizes of markers were chosen:

1. **Large markers** (1.5 cm)
2. **Medium markers** (1 cm)
3. **Small markers** (0.5 cm)

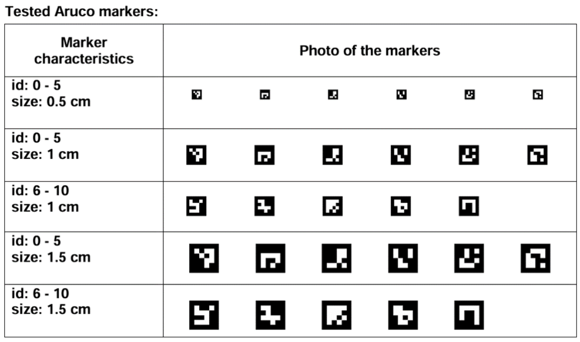

Figure 4.1: Tested Aruco markers

All markers were tested on a flat surface (on paper) and placed directly on furniture, simulating how they would appear during actual interaction with the application and users. Shown in Figure 4.2 and in Figure 4.3.

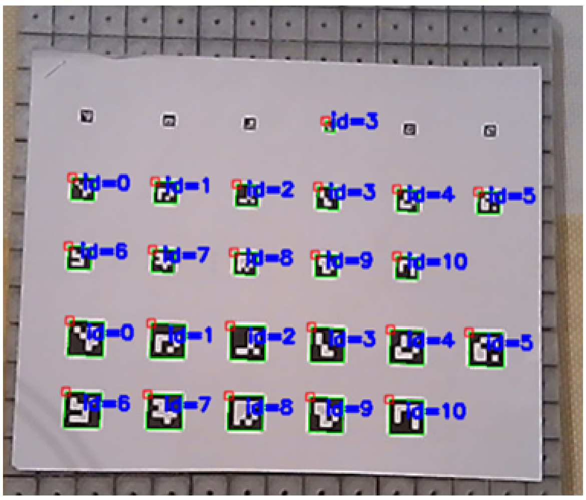

Figure 4.2: Tested Aruco markers on paper

The camera was placed 35 - 40 cm above the table with 3x3 haptic modules (each module is 5x5 squares) using a mobile phone stand. All the largest markers (1.5 cm) and the medium markers (1 cm) were detected. In a group of the smallest markers (0.5 cm), only one marker was detected.

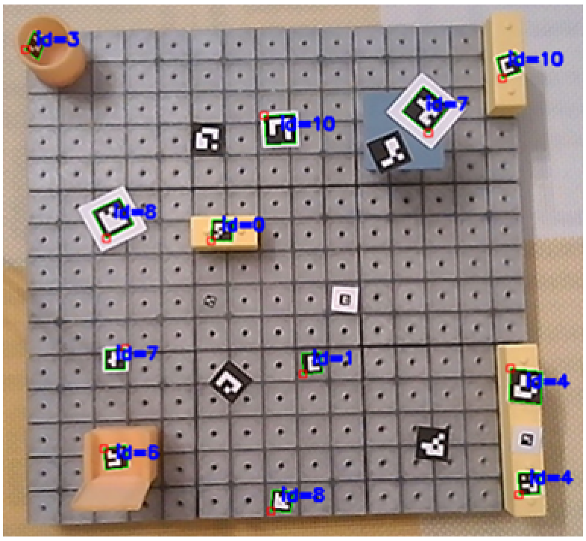

Figure 4.3: Tested Aruco markers on furniture

The optimal height of the camera above the system is approximately 35 - 40 cm above the work surface. This height is safe for the users with VI and the camera is able to detect all the necessary markers. For our purposes, the best size of the markers is a medium measures 1x1 cm, as they easily detectable and occupy a sufficient amount of space on the work surface.

4.1.3 Data transmission from camera to main application

To solve the problem of data transfer between the camera module (ArucoDetection) and the main application (HapticTiles), several communication protocols were considered [23]. In the end, the TCP protocol was chosen due to its reliability, ordered data delivery, and simplicity of implementation.

For the implementation of the TCP protocol, the *SimpleTCP* library [24] was used, which simplified the setup of both the client and the server.

The console application ArucoDetection acts as the TCP client, sending marker data (IDs and spatial information) over the network. The HapticTiles application contains the TCP server, which receives and processes these data in real time, allowing the user interface to provide immediate feedback based on the current positions of detected objects.

4.1.4 Audio feedback

The system provides spoken feedback to users on the correctness of object placement. This task was implemented using the built-in *System.Speech.Synthesis* library in .NET. [25]. This library provides straightforward access to speech synthesis functionality without requiring any external dependencies or internet connection.

4.1.5 Position mapping (coordinate transformation)

To accurately map the position of detected markers from the camera coordinate system to the virtual tactile map coordinate system, two machine learning models were trained using *ML.NET Model Builder* [26] with the Value Prediction scenario. Separate *LightGBMRegression* models were created for the X and Y coordinates. These models are utilized in the PredictArucoPosition class, which predicts the virtual position of each marker based on real-world coordinates and rotation.

For easier collection and storage of training data, a console application (GetTrainingData) was developed. This application takes user input via the console (including marker ID and spatial data in camera coordinate system) and saves it into CSV files. Approximately 500 data records were collected this way to train the models.

4.1.6 Summarization of implementation methods

To summarize, several key features were developed to support the application's functionality.

1. Interaction with the camera and detection of physical markers were made possible using the OpenCV library [21].

2. The SimpleTCP library [24] enabled seamless communication between different components of the system.

3. Audio feedback on the correctness of object placement was implemented using the built-in System.Speech.Synthesis library [25], providing immediate support for users.

4. Finally, machine learning models created with ML.NET Model Builder [26] allowed for accurate coordinate transformation, bridging the gap between physical marker positions and their virtual representations.

Together, these technologies made it possible to improve the CM externalization for visually impaired users.

Now, we will proceed to the next chapter, which focuses on evaluation of the developed application to ensure its functionality and usability meet the project goals.

Chapter 5

Evaluation

In this section, the developed application is tested in order to identify its strengths and weaknesses. The goal is to better understand how the current implementation performs and what aspects could be improved in future versions of such interactive systems to make them more effective and user-friendly.

To evaluate the application, a user study was conducted with four participants (P1–P4) aged between 39 and 51 (average age: 45). The group included one man and three women, with varying degrees of visual impairment described in Table 5.1 below:

Table 5.1: Participant in the evaluation of the tactile map system

ID	Gender	Age	Vision Description
P1	Male	47	Completely blind
P2	Female	39	One eye vision - 8%
P3	Female	51	One eye vision - 10% (able to distinguish contrasts and colors)
P4	Female	42	Completely blind

Before the testing began, each session included a short introductory phase consisting of an informal conversation (“icebreaker”) and a brief explanation of the purpose of the study.

The testing followed a predefined session guide consisting of five main tasks and one optional designed to assess how well users could explore, memorize, and reconstruct a tactile maps with and without audio feedback:

1. **Exploration of the tactile maps**

   During the first test, users explored tactile maps and described their CM of the space.

   - Goal: To familiarize participants with tactile maps and help them form a CM of the room layout.

2. **Reconstruction from memory (without correctness feedback)**

   Users recreated the layout using the same objects, guided only by basic instructions (e.g., ”Place the armchair and press the object”), without feedback on correctness.

   - Goal: To assess participants’ ability to recall and reconstruct the room layout based on memory and minimal instructions, without audio correctness feedback.

3. **Optional re-exploration**

   A short revisit of the tactile maps was allowed before continuing.

   - Goal: To minimize memory errors by allowing participants to briefly revisit the tactile maps before continuing.

4. **Reconstruction with active audio feedback**

   Users repeated the reconstruction task, now with audio feedback indicating whether the object was correctly placed or providing guidance such as ”move left” or ”rotate the object”.

   - To test whether the audio feedback improves accuracy and confidence in placing objects correctly, compared to reconstruction without guidance (Tasks 2 and 5).

5. **Minimal-instruction reconstruction (same as Task 2)**

   Users recreated the room based only on minimal prompts, without feedback on correctness.

   - Goal: To determine whether the audio feedback from the previous Task 4 improved the accuracy of participants’ CM.

6. **Free placement of a known real-world space**

   Reconstruction of a room in the participant’s home or office, based on their own experience.

   - Goal: To assess the usability and relevance of the application for reconstructing familiar real-life environments.

During the testing sessions, the participants shared their impressions and thoughts on the system, highlighting what they found useful, as well as aspects that they would like to see improved. It is important to emphasize that this project focuses primarily on the audio feedback on correctness function during the externalization of CM. Accordingly, the feedback related specifically to the audio guidance system is presented first, divided into strengths and challenges. Following this, other points of feedback are discussed, which may help inform future improvements of the system.

- **Strengths:**
  - Audio feedback was highly appreciated by participants P1, P2, P3, P4 as it helped them better understand the spatial arrangement of objects. Participants P1 and P2 noted that audio cues made it easier to orient themselves during the tasks.
  - Participant P1 also noted the clarity of rotation instructions. He appreciated that the system chose the most efficient way to correct object orientation — for example, suggesting a 90-degree turn in the opposite direction instead of a full 270-degree rotation, making the process faster and more intuitive.
  - Participant P2 emphasized how the system encouraged precision. During Tasks 2 and 4 (with minimal instructions), she was focused more on general placement — for example, placing the trash bin somewhere in the corner area, without worrying about exact coordinates. However, in Task 3 (with audio guidance), she found it particularly engaging to place objects exactly in the correct positions. The application's instructions motivated her to be more precise and attentive to detail, which she described as an interesting and satisfying experience.
  - Participant P4 expressed strong interest in the concept of tactile maps and found the audio feedback particularly helpful, as it supported her understanding the spatial relationships and distances between objects.
- **Challenges:**
  - Participants P1 and P3 found it difficult to understand certain phrases spoken by the system due to the speed of speech and use of English language.
  - For participant P3, Test 3 with audio cues appeared more challenging, as it required more precise placement of objects.

In addition to the main feedback points related to the developed system for supporting externalization, several other interesting observations emerged during testing that are worth highlighting. These points are also divided into strengths and challenges.

- **Strengths:**
  - Participant P4 proposed an alternative application for the system: To use it as an educational tool for young children, helping them learn about objects, their placement, and spatial relationships through a developmental game.

- **Challenges:**
  - Participant P3, who has 10% vision and is able to distinguish contrasts and colors, mentioned that having each object in a unique color would significantly aid orientation.
  - All participants experienced difficulties in accurately placing objects, particularly struggling to press the buttons located in the small holes.
  - Participant P3 had trouble distinguishing between the bed and the table and participants P1 and P2 suggested that having different textures to represent object types (e.g., fabric texture on the bed to represent blankets and pillows) would help better identify items such as wardrobes, dressers, chairs, and beds.

In the end of evaluation, a survey was conducted (which can be found in the Appendix A). The summarized results are presented in Table 5.2 below. Each question was rated on a 5-point scale, where:

- **5** = Rozhodně nesouhlasím (Strongly Disagree).
- **1** = Rozhodně souhlasím (Strongly Agree).

Table 5.2: Survey responses from participants

Participant	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10
P1	1	5	1	3	1	5	2	5	1	4
P2	3	5	2	5	1	5	1	5	1	5
P3	1	4	1	4	1	5	1	5	2	5
P4	1	5	1	3	1	5	2	5	1	4

The statements assessed various aspects of the system, such as ease of use, perceived complexity, learnability, integration of functions, and confidence while using the system.

Overall, participants tended to agree that:

- The system was easy to use (Q3) and well-integrated (Q5).
- They would like to use the system again (Q1).
- Most people would learn to use it quickly (Q7).
- And they felt confident using it (Q9).

On the other hand, some participants expressed mild agreement with statements indicating a need for assistance (Q4) or learning effort (Q10), particularly participant P2.

Statements related to system inconsistency (Q6) and awkwardness (Q8) received disagreement scores, which supports the system's consistency and agility.

These results indicate that participants generally found the system usable and approachable, though a few challenges remain, particularly in reducing complexity and improving onboarding for new users.

5.1 Summary of Findings

The overall qualitative feedback emphasized the crucial role of the audio feedback, which participants found helpful for better understanding spatial relationships and improving the accuracy of object placement. The rotation prompts were especially appreciated. The final task (reconstructing a familiar room) was reported to be the most engaging and enjoyable

At the same time, participants identified some challenges: difficulty interpreting certain audio cues due to speaking speed and language, insufficient color contrast in objects, and physical difficulties with precise object placement caused by hardware limitations.

In addition to the audio feedback-related points, several other interesting observations emerged during testing. Participants suggested that varying textures on objects could help differentiate furniture types, such as fabric textures to represent bedding. Some noted difficulties in accurately placing objects due to small button holes. Furthermore, participant P4 proposed alternative applications for the tactile maps, such as educational games for young children to learn about objects and spatial relationships.

The survey results indicate that participants generally had a positive experience with the system. They found it easy to use, well-integrated, and quickly learnable (Q3, Q5, Q7). Most participants were interested in using the system again (Q1) and felt confident while interacting with it (Q9). Also, some participants noted the need for technical support (Q4) and reported that some learning effort was required (Q10). Furthermore, they agreed that the system was simple (Q2), consistent (Q6), and user-friendly (Q8).

In conclusion, the findings confirm the system's general effectiveness while highlighting areas for future improvement, particularly in enhancing the audio interface, user adaptation, tactile design, and physical interaction elements.

Chapter 6

Conclusion

This chapter summarizes the key research results and reflects on how the defined goals were achieved. Additionally, directions for future work are outlined to guide further improvements and system development.

6.1 Conclusion

1. **Exploration of methods and technologies for externalizing CM:**

   The research thoroughly examined existing approaches and identified effective tools and methods suitable for externalizing CM for visually impaired users (results shown in Table 2.1).

2. **Analysis of needs and requirements of the target user group:**

   System requirements and user needs were identified primarily through a comprehensive literature review and analysis of prior research.

3. **Definition of system functional and non-functional requirements:**

   Based on the analysis, clear functional requirements (e.g., tactile map interaction, audio feedback) and non-functional requirements (e.g., usability, accessibility) were defined.

4. **Design and development of a method for CM externalization:**

   A novel approach combining tactile maps with adaptive audio feedback was designed to aid users in constructing accurate CM.

5. **Implementation of a prototype:**

   A working prototype combining the necessary hardware and software was created (see Figures **??**), allowing users to test it in practice.

6. **Evaluation of the prototype with users:**
   User testing demonstrated the system's effectiveness, particularly highlighting the benefits of audio feedback in improving spatial understanding and confidence (see survey results in Table 5.2). Challenges related to audio clarity, tactile differentiation, and physical interaction were identified, providing clear guidance for future improvements.

Building on these conclusions, the following section outlines potential directions for future research and development to further enhance the system.

6.2 Future work

This section presents points for future work based on the findings and test outcomes.

1. Improve audio feedback clarity and naturalness, with options for multiple languages and adjustable speed.
2. Add more distinct textures to tactile maps and objects for easier differentiation.
3. Refine hardware design to simplify object placement and button use.
4. Explore integration with other assistive technologies.
5. Develop training materials to help new users learn the system quickly.
6. Conduct testing with a larger and more diverse group of users.

Appendix A

Survey Questions

The survey was conducted in Czech and consisted of 10 questions related to the tested system. For each question, respondents provided answers on a scale from 5 to 1, where 5 means Rozhodně nesouhlasím (Strongly Disagree) and 1 means Rozhodně souhlasím (Strongly Agree).

For better readability, the survey is placed on the following page.

Prosíme Vás o vyplnění následujícího dotazníku. Jednotlivé body ve vztahují k Vaší celkové zkušenosti s testovaným systémem.

1. Rád bych systém používal opakovaně

Rozhodně nesouhlasím *Rozhodně souhlasím*

2. Systém je zbytečně složitý

Rozhodně nesouhlasím *Rozhodně souhlasím*

3. Systém se snadno používá

Rozhodně nesouhlasím *Rozhodně souhlasím*

4. Potřeboval bych pomoc člověka z technické podpory, abych mohl systém používat

Rozhodně nesouhlasím *Rozhodně souhlasím*

5. Různé funkce systému jsou do něj dobře začleněny

Rozhodně nesouhlasím *Rozhodně souhlasím*

6. Systém je příliš nekonzistentní

Rozhodně nesouhlasím *Rozhodně souhlasím*

7. Řekl bych, že většina lidí se se systémem naučí pracovat rychle

Rozhodně nesouhlasím *Rozhodně souhlasím*

8. Systém je příliš neohrabaný

Rozhodně nesouhlasím *Rozhodně souhlasím*

9. Při práci se systémem se cítím jistě

Rozhodně nesouhlasím *Rozhodně souhlasím*

10. Musel jsem se hodně naučit, než jsem se systémem dokázal pracovat

Rozhodně nesouhlasím *Rozhodně souhlasím*

Appendix B

AI Assistance

The utilization of AI tools complies with the guidelines and scope outlined in the document "Framework Rules for the Use of Artificial Intelligence at CTU for Study and Pedagogical Purposes in Bachelor and Follow-up Master Studies" (29.01.2024).

Used AI tools:

- **Chat GPT** (was used to check words, rephrasing, and self-studying).

Appendix C

Bibliography

[1] Miroslav Macik, Tomas Ivanic, and Lukas Treml. Interactive modular tactile maps of rooms for older adults with vision impairments. In Carmelo Ardito, Rosa Lanzilotti, Alessio Malizia, Helen Petrie, Antonio Piccinno, Giuseppe Desolda, and Kori Inkpen, editors, *Human-Computer Interaction – INTERACT 2021*, pages 321–330, Cham, 2021. Springer International Publishing.

[2] Nicholas A Giudice and Gordon E Legge. Blind navigation and the role of technology. *The engineering handbook of smart technology for aging, disability, and independence*, pages 479–500, 2008.

[3] Hana Majerova. The aspects of spatial cognitive mapping in persons with visual impairment. *Procedia - Social and Behavioral Sciences*, 174:3278–3284, 2015. International Conference on New Horizons in Education, INTE 2014, 25-27 June 2014, Paris, France.

[4] Mei Miao, Limin Zeng, and Gerhard Weber. Externalizing cognitive maps via map reconstruction and verbal description. *Universal Access in the Information Society*, 16(3):667–680, October 2016.

[5] Luca Brayda, Fabrizio Leo, Caterina Baccelliere, Claudia Vigini, and Elena Cocchi. A refreshable tactile display effectively supports cognitive mapping followed by orientation and mobility tasks: A comparative multi-modal study involving blind and low-vision participants. In *Proceedings of the 2nd Workshop on Multimedia for Accessible Human Computer Interfaces*, MAHCI '19, page 9–15, New York, NY, USA, 2019. Association for Computing Machinery.

[6] Christine Knauer and Norbert Pfeiffer. The value of vision. *Graefe's Archive for Clinical and Experimental Ophthalmology*, 246(4):477–482, 2008.

[7] Pablo-Alejandro Quinones, Tammy Greene, Rayoung Yang, and Mark Newman. Supporting visually impaired navigation: a needs-finding study. In *CHI '11 Extended Abstracts on Human Factors in Computing Systems*, CHI EA '11, page 1645–1650, New York, NY, USA, 2011. Association for Computing Machinery.

[8] João Guerreiro, Daisuke Sato, Dragan Ahmetovic, Eshed Ohn-Bar, Kris M. Kitani, and Chieko Asakawa. Virtual navigation for blind people: Transferring route knowledge to the real-world. *International Journal of Human-Computer Studies*, 135:102369, 2020.

[9] Hsin-Hsi Lai and Yu-Cheng Chen. A study on the blind's sensory ability. *International Journal of Industrial Ergonomics*, 36(6):565–570, 2006.

[10] ADcet. Inclusive teaching: Specific disabilities - blind and vision impaired, 2025. Accessed: 2025-03-16. Link: `https://www.adcet.edu.au/inclusive-teaching/specific-disabilities/blind-vision-impaired`.

[11] J. K. Bambara, V. Wadley, C. Owsley, R. C. Martin, C. Porter, and L. E. Dreer. Family functioning and low vision: A systematic review. *Journal of Visual Impairment & Blindness*, 103(3):137–149, 2019. (Original work published 2009).

[12] Rob Kitchin and Scott Freundschuh. *Cognitive mapping: Past, present, and future*. Psychology press, 2000.

[13] Raphael Kaplan, Nicolas W. Schuck, and Christian F. Doeller. The role of mental maps in decision-making. *Trends in Neurosciences*, 40(5):256–259, 2017.

[14] Robert M. Kitchin. Cognitive maps: What are they and why study them? *Journal of Environmental Psychology*, 14(1):1–19, 1994.

[15] Reginald G.GOLLEDGE, R. Daniel JACOBSON, Robert KITCHIN, and Mark BLADES. Cognitive maps, spatial abilities, and human wayfinding. *Geographical review of Japan, Series B*, 73(2):93–104, 2000.

[16] Edward C. Tolman. Cognitive maps in rats and men. *Psychological Review*, 55(4):189–208, 1948.

[17] R.M. Kitchin and R.D. Jacobson. Techniques to collect and analyze the cognitive map knowledge of persons with visual impairment or blindness: Issues of validity. *Journal of Visual Impairment & Blindness*, 91(4):360–376, July 1997.

[18] Loes Ottink, Bram van Raalte, Christian F. Doeller, Thea M. Van der Geest, and Richard J. A. Van Wezel. Cognitive map formation through tactile map navigation in visually impaired and sighted persons. *Scientific Reports*, 12(1), July 2022.

[19] Miroslav Macík and Meinhardt Branig. Mid-air haptic cursor for physical objects. In José Abdelnour Nocera, Marta Kristín Lárusdóttir, Helen Petrie, Antonio Piccinno, and Marco Winckler, editors, *Human-Computer Interaction – INTERACT 2023*, pages 563–572, Cham, 2023. Springer Nature Switzerland.

[20] Konstantinos Papadopoulos, Eleni Koustriava, and Panagiotis Koukourikos and. Orientation and mobility aids for individuals with blindness: Verbal description vs. audio-tactile map. *Assistive Technology*, 30(4):191–200, 2018. PMID: 28471302.

[21] OpenCV Team. Opencv - open source computer vision library, 2025. Accessed: 2025-01-12. Link: `https://opencv.org`.

[22] Michail Kalaitzakis, Brennan Cain, Sabrina Carroll, Anand Ambrosi, Camden Whitehead, and Nikolaos Vitzilaios. Fiducial markers for pose estimation: Overview, applications and experimental comparison of the artag, apriltag, aruco and stag markers. *Journal of Intelligent & Robotic Systems*, 101(4), March 2021.

[23] GeeksforGeeks. Types of internet protocols, 2025. Accessed: 2025-03-18. Link: `https://www.geeksforgeeks.org/types-of-internet-protocols/`.

[24] NuGet Contributors. Simpletcp 1.0.24, 2025. Accessed: 2025-04-01. Link: `https://www.nuget.org/packages/SimpleTCP/1.0.24?_src=template`.

[25] NuGet Contributors. System.speech 9.0.4, 2025. Accessed: 2024-11-13. Link: `https://www.nuget.org/packages/System.Speech/9.0.4?_src=template`.

[26] Microsoft Learn. Automate training with model builder, 2025. Accessed: 2025-05-18. Link: https://learn.microsoft.com/en-us/dotnet/machine-learning/automate-training-with-model-builder#which-machine-learning-scenario-is-right-for-me.

Appendix D
Attachments

As part of the bachelor thesis, a software module has been developed using C# and Visual Studio application. The archive BT_code contains the full source code organized into several independent projects:

- **ArucoDetection**

  The main application for detecting ArUco markers using a camera.
- **ArucoHelpers**

  A helper library that implements marker processing, ML-based position prediction, audio feedback, and network communication via TCP.
- **GetTrainingData**

  A tool for generating CSV training datasets for ML models.
- **RoomComparisonCustomComponent**

  A custom user interface component with audio interaction, designed for comparing room configurations based on detected markers.

This structure is illustrated in a diagram (Figure D.1), which was generated with the assistance of the ChatGPT AI chat.

```
BT_code/
├── README.md                      // Project description and usage notes
│
├── ArucoDetection/
│   ├── ArucoDetection.csproj      // Main project file
│   ├── ArucoDetection.sln         // Solution file
│   └── Program.cs                 // Program for marker detection
│
├── ArucoHelpers/
│   ├── ArucoHelpers.csproj        // Project file for helper library
│   ├── arucoHelpersDiagram.cd     // Class diagram (visual documentation)
│   ├── FurnitureArucoList.cs      // Contains data of detected furniture (marker)
│   ├── MarkerData.cs              // Defines marker data structure
│   ├── MarkerHandler.cs           // Handles marker processing logic
│   ├── PredictArucoPosition.cs    // ML-based position prediction
│   ├── Speech.cs                  // Audio feedback generation
│   ├── TCPClient.cs               // TCP client for networking
│   ├── TCPServer.cs               // TCP server for networking
│   ├── training_data/             // CSV data for Y-coordinate ML training
│   ├── training_dataX/            // CSV data for X-coordinate ML training
│   ├── X_ML2.*                    // ML.NET model files (axis X)
│   └── Y_ML2.*                    // ML.NET model files (axis Y)
│
├── GetTrainingData/
│   ├── GetTrainingData.csproj     // Project for training data generation
│   └── Program.cs                 // CSV export logic
│
└── RoomComparisonCustomComponent/
    ├── RoomComparisonUC/          // Folder for XAML structure
    ├── RoomComparisonUC.xaml.cs   // Custom UserControl with UI logic
    └── RoomComparisonViewModel.cs // ViewModel for component logic
```

Figure D.1: Schema of the attached archive BTCode.zip