

Table of contents

<i>Acknowledgments</i>	<i>¡Error! Marcador no definido.</i>
<i>Abstract</i>	<i>¡Error! Marcador no definido.</i>
<i>Thesis objectives</i>	<i>¡Error! Marcador no definido.</i>
<i>Research contribution and innovative aspects of the system</i> ¡Error! Marcador no definido.	
<i>Declaration</i>	<i>¡Error! Marcador no definido.</i>
<i>Abbreviations</i>	<i>¡Error! Marcador no definido.</i>
1. CHAPTER I: NAVIGATION SYSTEMS ¡Error! Marcador no definido.	
1.1 Motivation	<i>¡Error! Marcador no definido.</i>
1.2 Electronic Travel Aid Systems	<i>¡Error! Marcador no definido.</i>
1.3 Navigation Projects	<i>¡Error! Marcador no definido.</i>
1.4 Human stereo vision or stereoscopic vision ¡Error! Marcador no definido.	
1.5 Conclusions	<i>¡Error! Marcador no definido.</i>
2. CHAPTER II: ACOUSTICAL NAVIGATION SYSTEM FOR VISUAL IMPAIRED PEOPLE	<i>¡Error! Marcador no definido.</i>
2.1 System design	<i>¡Error! Marcador no definido.</i>
2.2 Requirements for the system	<i>¡Error! Marcador no definido.</i>
2.3 Sensor System	<i>¡Error! Marcador no definido.</i>
2.4 Artificial Vision System	<i>¡Error! Marcador no definido.</i>
2.4.1 Camera calibration	<i>¡Error! Marcador no definido.</i>
2.4.2 Image segmentation	<i>¡Error! Marcador no definido.</i>
2.4.3 Depth estimation	<i>¡Error! Marcador no definido.</i>
2.4.4 Object detection	<i>¡Error! Marcador no definido.</i>
2.5 Acoustical System	<i>¡Error! Marcador no definido.</i>
2.5.1 Stimuli	<i>¡Error! Marcador no definido.</i>
2.5.2 HRTF's measurement	<i>¡Error! Marcador no definido.</i>
2.5.3 Validation of the HRTFs	<i>¡Error! Marcador no definido.</i>
2.5.4 Sonification strategy	<i>¡Error! Marcador no definido.</i>
2.6 Communication Interface	<i>¡Error! Marcador no definido.</i>
2.6.1 Image processing interface	<i>¡Error! Marcador no definido.</i>
2.6.2 Sound interface	<i>¡Error! Marcador no definido.</i>
2.6.3 Communication interface design	<i>¡Error! Marcador no definido.</i>
3. CHAPTER III: SPATIAL SOUNDS ¡Error! Marcador no definido.	
3.1 Human ear	<i>¡Error! Marcador no definido.</i>
3.2 Sound localization	<i>¡Error! Marcador no definido.</i>
3.3 Monaural cues	<i>¡Error! Marcador no definido.</i>

3.4	Binaural cues	;	Error!	Marcador no definido.
3.4.1	Interaural Time Diference (ITD)	;	Error!	Marcador no definido.
3.4.2	Interaural Level Diference (ILD)	;	Error!	Marcador no definido.
3.4.3	Interaural Intensity Difference	;	Error!	Marcador no definido.
3.4.4	Cone of Confusion	;	Error!	Marcador no definido.
3.4.5	Precedence effect	;	Error!	Marcador no definido.
3.4.6	Reverberation effect	;	Error!	Marcador no definido.
3.4.7	Cross-correlation model	;	Error!	Marcador no definido.
4.	CHAPTER IV: SOUND SOURCE LOCALIZATION TESTS ;	Error!	Marcador no definido.	
4.1	Perception of the static sound source position ;	Error!	Marcador no definido.	
4.1.1	Sound sample	;	Error!	Marcador no definido.
4.1.2	Test participants	;	Error!	Marcador no definido.
4.1.3	Procedure	;	Error!	Marcador no definido.
4.1.4	Results	;	Error!	Marcador no definido.
4.1.5	Conclusion	;	Error!	Marcador no definido.
4.2	The influence of the inter-click interval on moving sound source localization tests	;	Error!	Marcador no definido.
4.2.1	Introduction	;	Error!	Marcador no definido.
4.2.2	Subjects	;	Error!	Marcador no definido.
4.2.3	Stimuli	;	Error!	Marcador no definido.
4.2.4	Equipment	;	Error!	Marcador no definido.
4.2.5	Procedure	;	Error!	Marcador no definido.
4.2.6	Results	;	Error!	Marcador no definido.
4.2.7	Conclusions	;	Error!	Marcador no definido.
4.3	General conclusions	;	Error!	Marcador no definido.
5.	CHAPTER V: OBJECT DETECTION THROUGH ACOUSTICAL SIGNALS	;	Error!	Marcador no definido.
5.1	Preliminary test I	;	Error!	Marcador no definido.
5.1.1	Subjects	;	Error!	Marcador no definido.
5.1.2	Procedure	;	Error!	Marcador no definido.
5.1.3	Results and discussion	;	Error!	Marcador no definido.
5.1.4	Conclusions	;	Error!	Marcador no definido.
5.2	Preliminary test II	;	Error!	Marcador no definido.
5.2.1	Procedure	;	Error!	Marcador no definido.
5.2.2	Results and discussion	;	Error!	Marcador no definido.
5.2.3	Conclusions	;	Error!	Marcador no definido.
5.3	Object detection and navigation tests II ;	Error!	Marcador no definido.	
5.3.1	Phase 1: Basic Learning Protocol (BLP) ;	Error!	Marcador no definido.	
5.3.2	Phase 2: Laboratory Tests	;	Error!	Marcador no definido.

5.3.3	Mobility Tests I.....	¡Error! Marcador no definido.
5.3.4	Mobility Test II.....	¡Error! Marcador no definido.
5.4	General conclusions of the navigation tests	¡Error! Marcador no definido.
6.	CHAPTER VI: CONCLUSSIONS	<i>¡Error! Marcador no definido.</i>
7.	CHAPTER VII: FUTURE WORK	<i>¡Error! Marcador no definido.</i>
8.	CHAPTER VIII: REFERENCES	<i>¡Error! Marcador no definido.</i>

Tables

Table 1.1 The main characteristics that affect mobility;Error! Marcador no definido.

Table 1.2 Direct Objective Measures for mobility ;Error! Marcador no definido.

Table 1.3 Electronic Travel Aids specifications ;Error! Marcador no definido.

Table 4.1 Localization performance summary statistics for all subjects (P1-P9) in frontal field. The percentage of the perception experiment is calculated on the basis of the six delivered sounds. ;Error! Marcador no definido.

Table 4.2 Evaluation of the minimum and maximum displacement for all participants as a function of the inter-click interval ;Error! Marcador no definido.

Table 5.0 Navigation accuracy..... ;Error! Marcador no definido.

Table 5.1 Results from the three trials of the Group A. ;Error! Marcador no definido.

Table 5.2 Results from one trial of the Group B..... ;Error! Marcador no definido.

Table 5.3 Results from one test for the four subjects with the improved version of the system ;Error! Marcador no definido.

Table 5.4 Results from 20 subjects for two runs for laboratory navigation experiment;Error! Marcador no definido.

Table 5.5 Results from the 20 subjects for the mobility test;Error! Marcador no definido.

Table 5.6 Mobility Test II results for the group A ;Error! Marcador no definido.

Table 5.7 Mobility Test II results for the group B ;Error! Marcador no definido.

Figures

- Figure 1.1 The long cane..... **¡Error! Marcador no definido.**
- Figure 1.2 Electronic Travel Aids classification..... **¡Error! Marcador no definido.**
- Figure 1.3 Lindsay Russell Pathsounder..... **¡Error! Marcador no definido.**
- Figure 1.4 Mowat Sonar Sensor..... **¡Error! Marcador no definido.**
- Figure 1.5 Nottingham Obstacle Detector (NOD) **¡Error! Marcador no definido.**
- Figure 1.6 Laser cane **¡Error! Marcador no definido.**
- Figure 1.8 The Polaron device..... **¡Error! Marcador no definido.**
- Figure 1.9 Sonic Torch..... **¡Error! Marcador no definido.**
- Figure 1.10 Sonicguide Mk II glasses **¡Error! Marcador no definido.**
- Figure 1.11 Talking Signs device **¡Error! Marcador no definido.**
- Figure 1.12 Talking Signs system function..... **¡Error! Marcador no definido.**
- Figure 1.13 Early conception of the Personal Guidance System;**¡Error! Marcador no definido.**
- Figure 1.14 Haptic Pointer Interface of the Personal Guidance System;**¡Error! Marcador no definido.**
- Figure 1.15 Functional components of the Personal Guidance system;**¡Error! Marcador no definido.**
- Figure 1.16 GPS Braille Note **¡Error! Marcador no definido.**
- Figure 1.17 Easy Walk system for navigation..... **¡Error! Marcador no definido.**
- Figure 1.18 Talk & Wayfinder **¡Error! Marcador no definido.**
- Figure 1.19 Tormes device..... **¡Error! Marcador no definido.**
- Figure 1.20 Trekker a GPS system for the blind and visually impaired;**¡Error! Marcador no definido.**
- Figure 1.21. TANIA navigation aid..... **¡Error! Marcador no definido.**
- Figure 1.22 The user with the SWAN system..... **¡Error! Marcador no definido.**
- Figure 1.23 SWAN architecture **¡Error! Marcador no definido.**
- Figure 1.24 EPFL prototype design and operation area;**¡Error! Marcador no definido.**
- Figure 1.25 The vOICe system components **¡Error! Marcador no definido.**
- Figure 1.26 vOICe functionality methodology **¡Error! Marcador no definido.**
- Figure 1.27 Last version of vOICe device..... **¡Error! Marcador no definido.**
- Figure 1.28 Tyflos prototype 2nd version components. a) Stereo cameras attached on dark eyeglasses and vibration array vest on the user abdomen, b) portable computer, c) microcontroller and PCBs, d) arrangement of the 4x4 vibrating elements inside the vibration array vest;**¡Error! Marcador no definido.**
- Figure 1.29 Forehead Sensory Recognition System components;**¡Error! Marcador no definido.**
- Figure 1.30 NAVI system..... **¡Error! Marcador no definido.**
- Figure 1.31 Human stereo vision **¡Error! Marcador no definido.**
- Figure 2.1 General working procedure of the system .. **¡Error! Marcador no definido.**
- Figure 2.2 Technical representation of the system components;**¡Error! Marcador no definido.**
- Figure 2.3 Real system composition: a) Components of the operational system b) Full device picture.
..... **¡Error! Marcador no definido.**
- Figure 2.4 The working area of the 3D-CMOS sensor with laser illumination implemented into a pair of glasses. The Red colour represents the infrared impulses emitted by the CMOS sensor; the blue colour represents the laser pulse reflection from the object. ... **¡Error! Marcador no definido.**
- Figure 2.5 Schematic representation of the Sensory System;**¡Error! Marcador no definido.**
- Figure 2.6 The picture of the Real-Time Assistance Prototype and the block diagram;**¡Error! Marcador no definido.**
- Figure 2.7 Stereo camera calibration method..... **¡Error! Marcador no definido.**
- Figure 2.8 Tool for eyeballing image capture from the head position sensor;**¡Error! Marcador no definido.**
- Figure 2.9 Typical image segmentation and object recognition scheme;**¡Error! Marcador no definido.**
- Figure 2.10 Example of image segmentation. Each column represents the segmentation of two different images..... **¡Error! Marcador no definido.**
- Figure 2.11 Depth estimation method..... **¡Error! Marcador no definido.**
- Figure 2.12 Depth map extraction from stereo images either side;**¡Error! Marcador no definido.**
- Figure 2.13 Object and free space detection..... **¡Error! Marcador no definido.**
- Figure 2.14 Spatial coordinates of the object **¡Error! Marcador no definido.**
- Figure 2.15 Spatial coordinate system a) represents the azimuth/elevation coordinate system consisting of a single pole oriented vertically. Azimuth describes the horizontal angular displacement due to rotation around the pole, with 0 ° azimuths at the front and 180° and -180° azimuths at the ear. b) describes the lateral/polar coordinate system. The system consists of a single pole passing through the two years.
..... **¡Error! Marcador no definido.**
- Figure 2.16 Signal spectrum for the Delta sound..... **¡Error! Marcador no definido.**
- Figure 2.17 Signal spectrum for the Synthetic Percussive sound;**¡Error! Marcador no definido.**

Figure 2.18 Signal spectrum for the Modified Synthetic Musical sound (Marimba); **Error! Marcador no definido.**

Figure 2.19 The anechoic chamber with small reverberation level and the robotic system. The walls and floor of the chamber are lined with sound absorbing wedges. The whole robotic system can be moved to place the loudspeaker at any location in radius of 5 meters. A chair for manikin is represented in a fixed platform. **Error! Marcador no definido.**

Figure 2.20 Sound generation and processing system. A represents the Huron system based on 40 analogical outputs and 8 analogical inputs and 8 DSPs 56002. The system was used for HRTFs measurements and experiments for mono and multi sources localization. B represents the computer where the HRTF's were processed and off-line processing of the spatialized sounds performed. **Error!**

Marcador no definido.

Figure 2.21 Test interface **Error! Marcador no definido.**

Figure 2.22 Test trajectories **Error! Marcador no definido.**

Figure 2.23 System integration components **Error! Marcador no definido.**

Figure 2.24 Communication interface design **Error! Marcador no definido.**

Figure 2.25 Communication interface design **Error! Marcador no definido.**

Figure 3.1 Human ear **Error! Marcador no definido.**

Figure 3.2 Iteraural Level Diference **Error! Marcador no definido.**

Figure 3.3 Interaural Intensity Difference **Error! Marcador no definido.**

Figure 3.4 Cone of confusion **Error! Marcador no definido.**

Figure 4.1 Click wave form with duration of 5ms. The x axis represents the time scale in seconds where the y axes represent the sound sample. The signal speed is 29,97 fps. **Error! Marcador no definido.**

Figure 4.2 HRTF coordinates presentation, where the $h_L(t)$ and $h_R(t)$ represent, respectively, the head-related impulse response HRIR at the eardrum for the sound source $x(t)$ at each ear, left $x_L(t)$ and right $x_R(t)$. The $x_L(t)$ and $x_R(t)$ could be calculated using the convolution integral $x_L(t) = \int h_L(\tau) x(t-\tau) d\tau$ and $x_R(t) = \int h_R(\tau) x(t-\tau) d\tau$, where τ is the delay. **Error! Marcador no definido.**

Figure 4.3 Schematic presentation of the sound. In both situations the click is of 5ms. In the first case, the click has been listened at the different interclick intervals ICI separated by a decision time T_d . In the second case, the click has been substituted by a train of six clicks. **Error! Marcador no definido.**

Figure 4.4 Mean estimation of the click location: a) Represents the perception of the single click and the perception of the train of clicks at 0° (center) at different ICIs; b) shows the click perception at -30° (left side) and $+30^\circ$ (right side); c) corresponds to the train of click perception at -30° (left side) and $+30^\circ$ (right side) **Error! Marcador no definido.**

Figure 4.5 HRTF wave form of 22050Hz sampling rate, and the length of 46ms of 8192 bit. In the x axis, the stimulus sample is represented. **Error! Marcador no definido.**

Figure 4.6 The anechoic chamber. The walls and floor of the chamber are lined with sound absorbing wedges. The whole robotic system can be moved to place the loudspeaker at any location in radius of 5 meters. A chair for manikin is fixed in a platform. **Error! Marcador no definido.**

Figure 4.7 Method for sound processing and reproduction; **Error! Marcador no definido.**

Figure 4.8 Sound trajectory example, direction from left to right. The x axis represents the azimuth where the 0 is the centre of the head, which is 0° . The -2.5 is the -32° at left side of the head and 2.5 respectively is 32° at the right side of the head. The y axis represents the distance from 0 to 5m; **Error! Marcador no definido.**

Figure 4.9 Experimental scenario. The user is seated on a chair in front of a computer. Hearing the sound through headphones he should draw the perceived sound trajectory in the paper **Error!**

Marcador no definido.

Figure 4.10 Average displacements in azimuth and distance for all participants; **Error! Marcador no definido.**

Figure 4.11 Sound trajectory for one participant for the ICIs of 50ms, 100ms, 150ms and 200ms. The red colour represents the heard sound trajectory drawn by the participant; the grey colour represents the real sound trajectory drawn by the computer. The x axes represent the azimuth, in which the 0 value is the centre of the head, the negative value are the values at the left side of the head and the values at the right side of 0 represent the azimuth values at the right side of the human head. -2.5 represents the 32° at left side of the head and 2.5 respectively the 32° at the right side of the head. The y axis represents the distance from 0 to 5m. **Error! Marcador no definido.**

Figure 5.1 Experimental scenarios: a) Single column detection; b) Two columns detection and pass through them; c) A wide wall; d) A column detection in front of a wide wall and e) Outdoor experiment **Error! Marcador no definido.**

Figure 5.2 Distance and volume recognition representation; **Error! Marcador no definido.**

Figure 5.3 Results of preliminary tests on auditory localization; (a) Time for sound perception, (b) Time for object detection and location..... **¡Error! Marcador no definido.**

Figure 5.4 Experimental scenario..... **¡Error! Marcador no definido.**

There were also individual differences in performances; some participants had little difficulty with the spatial sounds. In general, they performed very well on these trials, trying to have the best results on both tasks..... **¡Error! Marcador no definido.**

Figure 5.6 Trial trajectories for two situations. The red trajectory is for the case in which the participant was looking and analyzing the scenario moving from the left to the right. On the other hand, the case in which the participant was analyzing the situation moving the head to the left and right is represented in blue ink. The optimum trajectory is represented with black;**¡Error! Marcador no definido.**

Figure 5.7 Devices for navigation task: A) 3D-CMOS laser implemented on a pair of glasses, B) Headphones, C) Backpack with the electronics **¡Error! Marcador no definido.**

Figure 5.8 Headphones model used in the experiment. **¡Error! Marcador no definido.**

Figure 5.9 Experimental scenarios: a) Single column detection; b) Two columns detection and pass through them; c) A wide wall; d) A column detection in front of a wide wall and e) Outdoor experiment **¡Error! Marcador no definido.**

According to the time results of the Basic Learning Protocol experiment, we can conclude that great differences were registered both between exercises and groups. The results show that different exercises present different level of complexity. From the registered data, after the BLP finished, we can note that the exercise number 1 “Single column detection” was easy to do.**¡Error! Marcador no definido.**

Figure 5.10 Time for object detection for the seven exercises of the group A. The horizontal axes represent the seven exercises, whereas the vertical axes show the required times in minutes. The seven exercises data from ten subjects and the average times are presented. In each panel, the results are shown for one run..... **¡Error! Marcador no definido.**

Figure 5.11 Requested time for completing seven exercises of three runs. The seven exercises data from ten subjects and the average time are labelled. In each panel, the results are shown for first run (in pointed bars), for the second run (with horizontal bars) and finally the third run (with white and black angled bars). The best time results correspond to the minimum possible values. The horizontal axes represent the seven exercises, whereas the vertical axes show the time in minutes.**¡Error! Marcador no definido.**

Figure 5.12 The average time of the first run for all seven exercises from the groups A and B **¡Error! Marcador no definido.**

Figure 5.13 The average time for the seven exercises, for three runs carried out by the group A from DBSV..... **¡Error! Marcador no definido.**

Figure 5.14 Experimental scenario..... **¡Error! Marcador no definido.**

Figure 5.15 The real scenario of the experiment. The scenario was located in a hall of 258m². The trajectory is created by soft-box carton columns; a square made by carton boxes placed at the hall background was used as a wall. **¡Error! Marcador no definido.**

Figure 5.16 Registered walking time for four different runs of the groups A and B. In the case 1) the blind user completed the 14m labyrinth with the white cane. The 2, 3 and 4 are the runs with Acoustic Prototype. **¡Error! Marcador no definido.**

Figure 5.17 Registered walking time for two runs of the group B. In cases 1 and 3, the blind user completed the 14m labyrinth from the first time. Case 2 and 4 correspond to the repeated run with Acoustic Prototype. **¡Error! Marcador no definido.**

Figure 5.18 Example of the used mobility test I scenario of the group B.**¡Error! Marcador no definido.**

Figure 5.19 Example of graphical evaluation: Amplitude (dB) per distance (1-12) and per elevation (1-7) for one azimuth (0°, column 7) and for both channels left and right. The array of 13x7x12, at 48kHz **¡Error! Marcador no definido.**

Figure 5.20 Time performances for object detection. Abscissa represents the trials where the number 1 represent the first run of the group A, the number 2 is the repeated trajectory by the group A. The number 3 represent the mean time for the first trajectory of the group B, the number 4 show the mean time of the repeated trajectory by the group B. The 5 number illustrate the mean time of second trajectory completed by the group B and finally the number 6 represent the mean time of the repeated trajectory by the group b..... **¡Error! Marcador no definido.**

Figure 5.21 Average number of heats for all subjects for the first and second run. The 1 and 2 bars represent the average value of the group A where the bare 1 shows the average values for the first run and the bare 2 represent the average value of the second run. The bare 3 and 4 shows the average data for the group B respectively, where the bare 3 plot the average value of the first run and the bare 4 the results of the second run..... **¡Error! Marcador no definido.**

Figure 5.22 (a) Absolute walking time from Mobility Test I. The ten clusters of bars show results for the ten subjects from the group A as well as the mean across subjects. Results are shown for absolute walking time with the white cane (the blue colour), the absolute walking time for the first run (with magenta colour) and finally the absolute walking time for the second run (with yellow colour). The cluster of bars number 11 shows the mean time for ten subjects. (b) Errors from Mobility Test I group A are shown for the AWT1 and AWT2 for all subjects..... ¡Error! Marcador no definido.

Figure 5.23 Absolute Walking Time results from Mobility Test II. The eleven clusters of bars show results for the ten subjects as well as the average across subjects.¡Error! Marcador no definido.