AGH UNIVERSITY OF SCIENCE AND TECHNOLOGY

Faculty of Computer Science, Electronics and Telecommunications
Department of Electronics

Doctoral Thesis

MOBILE SAFETY SYSTEM FOR THE BLIND

WOJCIECH GELMUDA, MSc

Supervisor:
Professor Andrzej Kos

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To my Grandfather

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‘The roots of education are bitter, but the fruit is sweet’

Aristotle

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List of Symbols and Abbreviations

β – rotation angle [deg]

γ – suppression coefficient

$\dot{\theta}_b$ – the angle bias [deg] (Kalman filter)

θ_z – angle between R line and normal to the ground [deg]

$\dot{\theta}_z$ – angle from a gyroscope measurement [deg] (Kalman filter)

ω – angular frequency [rad/s]

λ – wavelength [m]

a – acceleration [m/s^2]

B – control model matrix (Kalman filter)

D – distance between the device and the ground [m]

d – distance [m]

E – amplitude

F – state transition model matrix (Kalman filter)

G – rotation matrix (Kalman filter)

H – observation model matrix (Kalman filter)

I – wave intensity [W/m^2]

I_0 – initial value of wave intensity[W/m^2]

I' – identity matrix (Kalman filter)

K – Kalman gain (Kalman filter)

l – length [m]

M – covariance (Kalman filter)

N – number of fringes

P – error covariance matrix (Kalman filter)

p – measurement noise (Kalman filter)

Q – covariance (Kalman filter)

R – range finder measurement [m]

S – innovation covariance (Kalman filter)

u – control input (Kalman filter)

v – velocity [m/s]

w – process noise (Kalman filter)

x – state (Kalman filter)

$\hat{x}$ – prediction of state (Kalman filter)

$\tilde{y}$ – innovation (Kalman filter)

z – measurement (Kalman filter)

AEM – Advanced Energy Monitoring

API – Application Programming Interface

CCD – Charge Coupled Device

CID – Cell ID

EA – Electronic Aids

EOA – Electronic Orientation Aids

ETA – Electronic Travel Aids

GPRS – General Packet Radio Service

IMU – Inertial Measurement Unit

IRRF – Infrared Range Finder

LAC – Location Area Code

LRF – Laser Range Finder

MCC – Mobile Country Code

MEMS – Microelectromechanical Systems

MNC – Mobile Network Code

MOBIAN – Mobile Safety System for the Blind

NEMS – Nanoelectromechanical Systems

PLD – Position Locator Devices

POI – Point of Interest

RFID – Radio-Frequency Identification

RSSI – Received Signal Strength Indication

SDK – Software Development Kit

WHO – World Health Organization

CHAPTER 1: INTRODUCTION

Today's world is filled with electronics thanks to the technological progress which is remarkable. As a result of a relatively inexpensive high volume silicon chips production, electronics is very common not only in high-end but also in low-end devices. In cooperation with mechanics electronic systems have evolved in the recent years. They are currently more sophisticated and what is important they can be really small, reaching microscopic (*MEMS*) or even nanoscopic sizes (*NEMS*). Therefore, future generations are going to be aided by hardly possible to be seen with the human eye devices in many fields, for instance, nanorobotics and medicine. However, this future is more or less distant. And what about the present?

As for the field of medicine and rehabilitation, researchers all over the world are successfully implementing electronic and electro-mechanic systems into disabled people's lives to help them to cope with everyday existence. There are always-improving artificial pacemakers, digital hearing aids, active prostheses, etc. There are prostheses almost for everything. However, the difficulties occur with designing medical and rehabilitation aids for the visually impaired people, taking into account their disability and the fact that humans perceive and recognize environment mainly using sight. The full restoration of vision is not possible with the knowledge we currently have, however researchers are working on it. Without supplying the blind with the information about the environment they are unable to live fully independently and what is most important they are unsafe while travelling between locations especially in unfamiliar environments and almost every blind person depends only on a white stick and remaining senses in those situations.

According to the World Health Organization (*WHO*) there are over 40 million blind people around the world. In many research facilities engineers are developing devices to help blind people gain full independence in their everyday lives and assure them of safety during moving. There have been successful attempts of creating devices for obstacle avoidance and distance measurement, using add-ons for common white sticks or devices replacing them. Those applications usually employ infrared or ultrasonic sensors or both. Nevertheless, there is still some dangers for blind people while they are moving, especially in urban environments, the perfect examples of which can be holes in pavements or road excavations.

Motivation

The mainstream, electronic system high-volume manufacturing made it possible to sell sophisticated devices at reasonable prices. The phenomenon of personal computers, mobile phones and tablets has led to a relatively large percentage of those devices even in the third world countries, especially among young people and students. Unfortunately, the numbers do not look so optimistic when it comes to specialized or even custom made equipment.

When I was working on my MSc dissertation, an electronic system for blind people and during the first year of my PhD studies, I had a chance to meet some of visually impaired people and speak with them about their problems and needs. I have come to realize that developing electronic aids for blind people requires a specific approach. Some solutions commonly used in electronic devices for people with normal vision, especially in user interfaces, are not efficient or even impossible to use by blind people.

There are many different objects, scenarios or even mental disorders that can cause some potentially hazardous situations for blind people. Some of them are described in one of the sections below. Electronic devices, if designed properly, can eliminate or minimize some of the dangers.

There is the Special Educational Centre for Blind and Visual Impaired People in Kraków. Kids, teenagers, their teachers and patrons are very eager to assist and share their ideas and problems with others in order to help in creating electronic assistant devices for blind and visually impaired people. Close proximity to this center and cooperation makes it easier to develop the needed devices and seeing blind people everyday in the city allows for a better understanding of their needs and behavior. In addition to the previously mentioned, there is strong motivation and satisfaction when doing research, which can help the part of the community in a city you live in.

Even with an approach focused on blind people while designing electronic device for their use, some problems occur. One of the major problems is that practically all electronic or mechanical aids for blind people are very expensive due to a small production volume. The average price of Braille readers or displays is similar to a new small car price. Special centers, like the one in Kraków, do have those types of readers, but only few blind people can really afford them for a personal usage. Thus, the research should also focus on the end price of the electronic aid device in order to help all the blind people in the world, especially in the third world and developing countries where average people simply cannot afford high price devices and governmental donations and funding hardly exist.

Aim of dissertation

Blind people have to deal with everyday tasks, which may seem trivial to people with unimpaired vision. One of those tasks is to safely navigating and move between places, especially in urban areas, and frequently in unfamiliar areas. There is a great number of dangerous objects and situations in which a person can be harmed when he or she is walking from home to work. This number is even greater for blind and visually impaired people.

One can say that those people can take a taxi to get from one place to another or someone can assist them, but for most blind people this is not a solution. Usually, blind people cannot afford to use taxis on daily basis. More than that they want to live an independent and normal life. And most of all, there are also dangerous places inside buildings that can be harmful for blind people, like for instance stairs.

Many talks with visually impaired people, their parents and teachers, have made it clear that blind people trip and fell over or bump into something on daily basis and this is nothing unusual for them. Being most of the time with their white sticks they are able to sense the obstacle and safely avoid it. However, there are numerous obstacles that are difficult to be ‘noticed’ with the white stick, for example road holes and all the obstacles on a chest and head level.

The aim of this dissertation is to design and create a device to match the described needs of blind people. The device is to detect dangerous obstacles, road holes and stairs and in addition to that to inform blind people about this detection in a way that does not affect their hearing perceptual ability. This device is to be light-weight, mobile and withstand at least 1 day of standard operation without any battery recharge.

The indirect aims that are crucial for achieving the main objective are in particular the following:

- to study the blind people needs regarding electronic aids,
- to analyze the available electronic aids solutions for the blind, their pros and cons,
- to create methods to obtain information from surroundings in order to detect obstacles,
- to develop methods to detect hazardous road holes and obstacles,
- to make an overview of existing electronic components, especially low-power ones,
- to design, prototype and test the device that will detect and inform blind users about the mentioned objects.

Thesis

The aim of this dissertation is compressed and presented as the following thesis:

It is possible to detect and inform about hazardous obstacles for blind people, in particular road holes and head level objects, using user-friendly electronic mobile system, when a blind person is walking.

Thesis outline

This dissertation content can be outlined as follows.

CHAPTER 2 makes an introduction about safety problems blind people have to deal with on daily basis. This overview has been created based on literature and consultations held with blind people and their teachers from the Special Educational Centre for Blind and Visually Impaired People in Kraków. This particular chapter helps to realize the vast differences between safety issues of blind people and of people with an unimpaired vision.

The extensive review of already existing and in-progress electronic aids for blind people is presented in CHAPTER 3. The categorization helps to present the main branches of electronic aids types. This chapter underlines the fact that many issues are still not resolved and much has to be done in the direction of increasing the safety level of blind people.

CHAPTER 4 presents ways to obtain terrain information from the surroundings and leads to conclusions in respect to which technique has to be chosen in order to fulfill the established goals. The stabilization algorithm is carried out and preliminary results are presented from the working device prototype. The chapter is focused on creating a solution for a successful detection of all the road holes and obstacles, which can appear on the blind person path.

CHAPTER 5 deals with other common obstacles that are hard to detect with help of just a white stick – the obstacles on a chest and head level. A specialized multichannel ultrasonic range finder is presented.

The issue of transmitting the information about detected obstacles is discussed in CHAPTER 6. A vibrating bracelet solution is introduced. Its functionality can be extended and it is shown that by modulating a vibration signal, a wide spectrum of commands and information can be transmitted and properly interpreted by blind users in real-time.

The prototype device that was used by blind people from the Special Educational Centre for Blind and Visually Impaired People in Kraków is mentioned in CHAPTER 8. Various tests with a help of the blind and results are also presented. The users' opinions on the device shows that the methods proved to be effective and the device gained interest and sympathy of the young blind people.

Other subsystems and work implemented as a part of the *MOBIAN* project are mentioned in CHAPTER 7. In CHAPTER 9 final conclusions and opinions are presented.

CHAPTER 2: BLIND PEOPLE SAFETY ISSUES

Not only humans, but also animals, gather information from the environment through their senses. These senses operate like sensors in an electronic systems. Based on the information from the senses, brain can process the data and result in some reaction in response. Sometimes the reaction is immediate as a result of a reflex. Furthermore, the brain allows to memorize some behavioral patterns in order to react accordingly in the near future. As an example: do not touch a hot pot or you will get burned. The following interaction with the surroundings is a basic mechanism for avoiding dangerous situations on daily basis and the senses are the main parts in this respect.

Sense of sight

Today's life as we know is based on visual signs. Practically all the important information needed to move independently through an average person's day is provided by its sight. A person is able to see objects, determine an approximate distance, distinguish between a hole and a bump on a road, detect and recognize an important element from its background or simply read text information from books, posters, etc. Most of the actions, if not all, allow people to gather information and give them time to react before they approach some objects. Furthermore, there are many devices that help people gain important information that they would not be able to learn from the closest environment in their field of view, such as navigation systems. There are also many devices that help people stay safe and avoid accidents, i.e. street lights or road signs. But neither of them is well suited for visually impaired people. Needless to say, there are special audio signals for blind people near some pedestrian crossings and devices which help visually impaired people to avoid obstacles do exist, but all the measures are not sufficient to keep them safe and well informed about surrounding environment.

There are many causes of deteriorating vision or blindness. Nevertheless, the most common causes are diseases, according to the World Health Organization (*WHO*). A survey taken in 2002 [Res04] showed, that cataracts is still the leading disease related to blindness. The other reasons can be the following:

- cataracts (47,8%),
- glaucoma (12,3%),
- age-related macular degeneration (8,7%),
- corneal opacity (5,1%),
- diabetic retinopathy (4,8%),
- childhood blindness (3,9%),
- trachoma (3,6%),
- onchocerciasis (0,8%),
- others (13%).

Apart from diseases, people around the world suffer from a partial or full loss of sight due to some genetic defects and pregnancy-related issues. Additionally, chemical poisoning, for instance from methanol, can lead to the blindness. Another sources of – mostly partial – loss of vision are various accidents where the whole or part of the eyeball is damaged. This mainly occurs while operating some machinery and in most cases could be easily avoided by respecting safety rules and wearing protective glasses. Also, there are still some regions around the globe where tortures and punishment by making a person blind are practiced.

Since diseases are responsible for making people blind, it is clear that the majority of all the blind people live in the developing countries. Creating better living conditions, better healthcare and providing food resources would certainly take the number of blind people to the level of the one that is across developed countries.

Environment

Regardless of the area of residence of a blind person, be it an urban area or countryside, the blind person’s environment can be divided into the indoor and outdoor when safety issues are taken into consideration.

Blind people feel safer in closed space, especially in places that they know well and they had been previously in and therefore have memorized their topography. These places are, for instance, their home and workplace, schools, shops. Blind people move faster and more confident there. In addition to that, these places do not often change their inside layout, so the risk of an accident is lower. The outdoors on the other hand are much more dangerous for blind people. Constant changes, unknown surroundings, heavy machinery, car traffic and the fact that a lot of information from the environment is passed through the sense of sight – all of these factors increase the possibility of an accident, injury or even death.

Additionally, consultations with children and teachers from the Special Educational Centre for Blind and Visually Impaired People in Kraków have shown that even such outrageous actions like assaults and robbery, in particular smartphones stealing, where blind people become victims, are very common nowadays. This is due to the fact that the thief is not likely to be identified.

Despite all the potential risk and accidents blind people want to be involved in a community and social life and travel from one place to another, they simply do not want to be compared to outcasts. They also want to be as independent as possible. That is one of the reasons why blind people are very open to all the electronic aids, navigations, obstacle detectors and other devices that could help them and increase their safety. The vast range of electronic devices for blind people is described in CHAPTER 3.

Most common accidents

Since blind people do hardly operate heavy machinery, they rarely participate in car or other machine accidents. Nevertheless, blind people more frequently than people with normal vision, take part in person-to-person or person-to-object collisions. In fact, those collisions are so common on the daily basis that blind people find they normal – as long as these bumps do not harm them or put their lives in danger.

Consultations held with blind people from the Special Educational Centre for Blind and Visually Impaired People in Kraków have shown that the most common accidents affecting blind people are the ones when they trip and fall due to holes and bumps in the ground and also injuries after blind people hit their heads against an object on their head level. These obstacles are very difficult to spot only with a white stick, yet they are commonly present in blind people close surroundings in both urban areas and country sides.

Forasmuch, blind people are enthusiastic about electronic aids which would help them to avoid the mentioned hazards, unfortunately none of the existing ones does that or provides a high reliability.

CHAPTER 3: ELECTRONIC AIDS FOR BLIND PEOPLE

For a very long time the technology advancement has had the noble intention to improve people's safety and to make their live easier. That also applies to the visually impaired people. Since the well-known white cane does not provide the desired reliability and functionality and according to, for example, [Far10], [Lee13b] and [Mau08], guide dogs are relatively expensive to be trained and have their own limitations, engineers in many science centers have been working on some electronic aids and complex systems for blind people. Apart from simple devices which, for instance, are able to check and tell a color of some surface and fabrics, or to index and then recognize objects with a use of *RFID* tags [Her08], there are devices that help blind people safely move around in known and unknown areas. These devices could be divided into the following three main categories [Dak10]:

- Electronic Travel Aids (*ETAs*) – those devices gather and process partial data from an environment in order to provide a blind person with the information sufficient for a safe passage,
- Electronic Orientation Aids (*EOAs*) – these devices help a blind person to find a direction of movement while walking from one point to another,
- Position Locator Devices (*PLDs*) – those devices with help of the *GPS*-like, *GSM* and *Wi-Fi* technologies make it possible to locate a blind user, for example, on a digital map and to navigate them to their final destination.

Although, many devices could be put into these categories, some systems for blind people due to their complexity fit into two or even all three of mentioned descriptions. Therefore, in this chapter, another kind of categorization is presented.

Categorization of electronic aids for blind people

Although, there are many ways to categorize electronic aids for the blind, it seems appropriate to analyze them from a technical point of view, focusing mainly on elements and methods that have been used and also on research novel ideas implemented, rather than devices' impact on the market, commercial success or price.

WHITE CANE SUBSTITUTES AND ADDONS

Almost every blind person uses a white stick of some kind. White sticks come in different types, endpoint shapes and sizes. They are also relatively low-priced as for assistive aids, so even small visually impaired kids are being taught how to use them. Blind people are used to white sticks and they feel more comfortable and safe while traveling with them. Therefore, some electronic aids (*EAs*) use white sticks as a carrier.

Addons to white canes should not compromise the weight of white canes and restrict their movements. Usually, in this kind of a solution a white stick can work as *RFID* reader [Far10], ultrasound obstacle detector [Ant13], [Cal10], [Her08], [Kos10] or as a carrier for other sensors [Sin13].

Since blind people are so much used to white canes, it is problematic to create a device which would provide such safety and high reliability to convince visually impaired persons to lay off white sticks and switch to electronic devices when travelling. Nevertheless, there are many devices that can assist blind people in order to improve their safety while walking. There are obstacle detectors based on ultrasonic transducers, infrared diodes or both [And08] and simple navigation aids that employ accelerometers [Bou06] and camera [Tap13], [Tia13]. Engineers are currently working on complex systems for blind people navigations [Bor11], [Dun10], [Sek11], which once perfected could replace popular white canes.

SINGLE AND MULTI-SENSOR DEVICES

Electronic devices for blind people varies in their basic functionalities. There are devices which serve only one purpose, for instance, obstacle detectors [Vil12] or *GPS* based locator and navigations like 'Trekker *GPS* system' [Pat10]. Such devices usually employ only one type of sensors. This approach is cost-effective and helps to develop and produce low-priced devices. This is very important especially for visually impaired people in the developing countries. However, it is hard to collect all the relevant information about a blind person's surroundings with help of only one type of sensors. Therefore, by using more sensor types, a functionality of the *EA* can be extended. This multi-sensor approach compensates limitations of one data type. Detecting obstacles only with an ultrasonic rangefinder does not assure high reliability due to the fact that ultrasonic waves reflect poorly from some types of surfaces and also a returning wave amplitude is highly dependent from the surface inclination [Gel10]. On the other hand, an infrared rangefinders are fragile to transparent surfaces. Thus, for the obstacle detection it is wise to use a multi-sensor approach and use both the infrared and the ultrasonic technique [And08]. This method, called a sensor fusion, provides better reliability and safety for a blind user. This is the case where different sensors types supply the same data – the distance from obstacles – but there are also devices that employ sensors which are able to provide other data from the environment. The implementation of a *GPS* module and *POI* database [San10] helps to navigate blind people, especially in urban environments, and inform about both dangerous objects and safe locations like pedestrian crossings. This type of sensor fusion increases safety in the blind people navigation systems. Some solutions also use video cameras both in a single mode [Buj08], [Jie10], [Pun13] and in stereoscopic mode [Fer10], [Oli13]. These approaches employ image recognition to get information from an environment in a way similar to a human sight and they can be used in addition to the mentioned sensors to work separately or mutually. Complex systems for blind people often use accelerometers, gyroscopes and compass [Bar10a], [Bar10b], [Bri11], [Sch11] to increase *GPS* data precision, to monitor blind person movement and position, stabilize other sensors measurements or filter the acquired data.

AUTONOMOUS DECISION AND NAVIGATION CENTER BASED DEVICES

It is safe to say that all *EAs* for blind people evolved from the fact that a simple white stick does not assure enough safety during walking. One way to overcome this issue is to assign a guardian to a blind person, who could guide and navigate them. This is the perfect solution, however not every blind person has one that could be the guardian and take care of the blind person around the clock. As for the navigation safety problem, guide dogs are being used. Nevertheless, guide dogs have their limitations, for instance, they are not cheap to be trained and the special training takes several months to be completed. Other way to increase the safety level is that a blind person gets around only in familiar, well known environments. However, even on everyday road from home to work or school, some possibly dangerous scenario elements are likely to change, like cars and road excavations occurrence or traffic lights. Yet, blind people do not want to give up normal life and want to go through life as independently as they can. That is why various *EAs* – based on a guardian technique and also autonomous navigation devices – have been designed to help blind people in this respect.

Most of the developed *EAs* are based on autonomous decision operation. Multiple sensors swipe the environment to gain all the important data, for instance, a visual image, blind person's position and one's movement, distance from obstacles, etc. The data is processed and used for navigation [Kam10], walking assistance [Mor12], [Son10], human and object detection and recognition [Kum11], [Yan14]. These devices are usually based on fast *FPGA* and *MCU* chips to handle real time computations, image processing, objects recognition and decision algorithms. In some cases they also have access to large databases of image samples or *POI*. The main advantages of these solutions are the following: the remote human guidance is not necessary and a blind person is relatively independent. There are also devices which employ all or some of the mentioned sensors but the decision making process and assistance are performed by some remote human operator [Vit10], [Vit11]. This feedback is often being done over *GPRS* or other radio connection [Buj08] and its presentation is through voice commands, sound or tactile signals [Ada13]. A blind person can request for assistance whenever needed. These solutions assure of a high level of safety and very detailed, strict and user-friendly guidelines. Nevertheless, a remote human operator is necessary.

SELF-ORIENTING AND LOCALIZATION BASED DEVICES

People mainly use vision in their everyday navigation tasks. Thanks to the sight a brain can obtain the important data from the environment, process this data and make a decision. There are also many aids to help people in navigation, for instance, regular maps, *GPS* devices and road signs. All those 'things' are helpful only when a person's vision is not impaired. That is why *EAs* for blind people have to gather all the important data, make decisions and supply users for selective, important information, warnings and alerts.

Various *EAs* use only a self-orienting technique in navigation. This means that only local environment is scanned. A global position or any maps and *POI* are irrelevant. Usually, these are all kinds of objects detectors and obstacle avoidance. Some devices use only ultrasounds or infrared beam to detect and inform about obstacles, like in [Cal09]. Other *EAs* employ video cameras and image processing to recognize objects of interest [Big10], [Chi11], [Kar11], [Udd05], [Sol11], [Jie10] or even people's faces [Kra10], [Kum11]. Usually, in those kinds of systems the distance from the recognized objects is important. For this reason, the stereoscopic vision [Che10b] and infrared based ranging [Bos06], [Mat10], [Mol09], [Ued06] are being used.

The second group of *EAs* is based on cooperation with external systems for localization purposes. Some solutions implement *RFID* tags into the environment to help navigate blind people and avoid or inform about various objects [Che10a], [Chu08], [Fag11], [Gan10], [Moo10], [Mur11], [Saa09], [Tan11], [Wic13] – even to play games [Lee13a]. Although, embedding *RFID* tags into large size environment can be costly, it is a suitable solution for indoors and campuses [Alg13]. In some cases, an existing system network can be used, for instance, *Wi-Fi* hotspots [Alh08], [Say09], [Ven09] or *GPS* signal [Bri11]. Both those solutions usually use *POI* or map of some kind for guidance. Often maps developed for people with normal vision is not suitable for navigating blind people and that is why special maps with customized *POI* and a changeable level of details are being used [Zha10].

Some systems employ both a self-orientation and external localization method to acquire more accurate data, compare detected objects image only with object database bound to the precise global location or maintain a position fix when one of the used methods is unavailable, for example the lack of *GPS* signal in tunnel [Bar10b].

AUTONOMOUS AND SERVER BASED COMPUTATION

EAs, both attached to white canes and external ones should be light weighted and relatively small. They should be comfortable and safe to wear. On the other hand, *EAs* must be low-power and last on batteries at least one day without charging. Batteries capacity and weight can be a disturbing problem for mobile *EAs*. Due to this some devices drop power demanding computations on remote computational servers. Generally, if a functionality of the *EA* is large, there is lots of data from multiple sensors. The easy way to save energy on mobile device is to send data to a server and wait for processed data or a navigation decision. Other types of devices that utilize this method are the ones that employ massive databases for navigation or image recognition, like for instance, geographic information [Far10], large amount of *POI* frequently updated [Kam10], navigation routes [Chu08], databases of road signs, characteristic buildings or shapes specific to a location or when *EAs* are using contents available online, like Google Maps, Quick Response Codes and *RFID* tags database [Gan10].

However, the mentioned methods save energy and at the same time maintain wide spectrum of functionality, sending large amount of data through *Wi-Fi* or cellular networks creates delays. Therefore, this is not the best solution for *EAs* which should work as real-time systems and provide reliable response in a deterministic, short period of time. That is why some electronic systems for blind people do all the computations by themselves. Usually, in those solutions autonomous work compromise a broad functionality, yet in some *EAs* real-time work is a must. Generally, they are obstacle detectors [And08], [Liu06], object recognition devices [Chi11], simple computer vision based systems [Jie10], navigation aids [San10], etc. The quick alert about possible threats gives blind users time to react and avoid tripping or hitting against some objects.

A flexible solution is a combination of methods mentioned in this section in one device in such a way that safety-critical, real-time modules work constantly and modules which involve heavy computations can be enabled on demand.

SIGNALING METHODS

In most navigation systems, all the important data is presented with help of a display of some kind, often supported with voice commands. Since this approach is futile for *EAs* for blind people, some other signaling methods are being implemented.

The most common way to pass information to blind users is the use of voice commands. There are several domains where this type of signaling is helpful, for instance, web browsing [Ale07], [Gho10], [Sal07], banknotes, coins [Sir09] and signage recognition [Hai11], etc. A synthesized, pre-recorded or live speech and also other acoustic signals are often being used in some navigation systems for visually impaired [Bha12], [Fag11], [Kum11], [Vit10], [Wen11]. Although, this type of signaling is the most natural for blind people and shortens the adaptation time for a new device and learning period, it suppresses other acoustic signals from the environment. This could be potentially dangerous for a visually impaired user, therefore, other signaling methods are also being applied.

Blind people often recognize objects by touching them. This helps them to identify shapes or read Braille signs. In [Mai05] there is a dynamic, tactile map presented. Mechanical matrix is able to display graphical shapes, navigate by means of straight lines or arrows to indicate direction or display pre-programmed characters to indicate a specific obstacle or place. Another type of signaling for blind people is a heat based matrix [Bor07]. It uses small Peltier modules. Users are able to distinguish between cold and warm points when a modules touches skin. The matrix is able to display shapes and even simple animations to represent the environment, therefore, it is a suitable user interface for visually impaired people.

There are also simple methods to indicate specific objects of interest or their distance from the user. The common approach is the use of vibrating motors [Dak10], [Str09] and modulate the signal impulses number and their length. There are also prototype interfaces where signaling is done through a voltage or current stimulation of user’s skin or tongue by electrodes, like in [Ech10], [Ngu13].

There have been successful medical trials where visual data from the environment was transmitted directly to a human neural system. Since those types of experiments are not widespread and they are highly invasive, they are not a matter of this dissertation.

CHAPTER 4: PATH FORM MEASUREMENTS

People with normal vision base their perception of surroundings on the sense of sight. People sometimes tend to take this sense for granted, because ever since they can remember, this natural recognition tool has always been available for them. With their eyes as sensors and a brain as a computational system, people can receive information about surroundings, process it and then make decisions. Recognizing objects and distances are relatively easy with a sense of sight. Therefore, walking safely, avoiding obstacles or dangerous objects is in a way natural for humans with an unimpaired vision and usually being done without conscious thinking. It is like a reflex.

A very different assessment is from a blind or any other visually impaired people perspective, both blind from birth and blind as a result of an accident of some kind or some disease. Granted, senses other than sight can be sharper among blind people, nevertheless these senses in most cases cannot compensate for a lack of vision, especially, when a blind person is walking.

The most common aid for visually impaired people is a white stick. Its role is bidirectional. A blind user can obtain some information from the environment and also inform other people about the blind person presence. A range of a white cane is a couple of steps at best. It is not far comparing with a range of sight. Nonetheless, is allows blind people to spot and focus on obstacles in the nearest area. Blind people, when walking, sweep the area in front of them with help of a white stick. In most cases it helps them detect and avoid obstacles. However, if a hole or a road imperfection occurs, blind people can easily trip or fall and this can cause severe health damage, or is some cases even death. Sweeping with a white cane does not ensure high reliability of detecting mentioned road holes, bumps or even stairs. Therefore, these threats are very dangerous for blind people. There is a solution to overcome this issue and it can be done by implementing the *RFID* tags into the outside infrastructure and embedding *RF* antenna into a white stick to inform blind people about holes, curbs or platforms [Far10]. Nevertheless, it is rather an expensive approach and cannot be applied in every town or city and especially not in developing countries, not to mention in case of random road excavations. Another solution is to scan the path area in front of a blind person for possible dangerous objects, holes or other road defects.

Real-life path scanning methods

There are many ways to perform a path form check to look for imperfections or obstacles. Most of them use some sort of distance measurements techniques or stereoscopic imaging and every method has its own pros and cons. In this section, some approaches are described from the perspective of a possible usage in aiding systems for blind people.

LASER AND IR RANGEFINDERS

Light can be perceived as a wave or as particles due to its wave-particle duality. Like all waves, light is a subject to a diffraction and an interference. In a linear medium, multiple waves that come from different sources interfere with each other in some point *C*. If two waves with identical amplitudes (*E*), wavelengths (λ) and corresponding phases meet in a point C and also the waves have different sources (these sources' distances from the point C are $d_1 = \lambda\varphi_1$ and $d_2 = \lambda\varphi_2$), the waves superposition in the point *C* can be described with (1).

$$f(C) = Esin(\omega t + \varphi_1) + Esin(\omega t + \varphi_2) \tag{1}$$

Therefore, the wave is amplified to $f(C) = 2Esin(\omega t)$ where $\varphi_1 - \varphi_2 = 2\pi k$ and suppressed to $f(C) = 0$ where $\varphi_1 - \varphi_2 = (2k + 1)\pi$ (*k = 0, 1, 2, ...*).

One of the possible applications of the light interference is a distance measurement technique. In a device a laser light pointed to a beam splitter can be splitted into two identical beams. One of these beams goes directly to a fixed-distance mirror and is reflected back (the reference beam). The other beam travels other path and is reflected back after encountering a mirror or an obstacle (the signal beam). The combination of those two beams creates an interference pattern in the detector. The phase shift carries the information about optical path. Knowing the wavelength of the source light λ and the number of fringes from the interference image *N*, the distance *Δl* can be calculated with (2).

$$\Delta l = N\frac{\lambda}{2} \tag{2}$$

Laser or *IR* range finders (*LRF* or *IRRF*) are devices that use light of the specific wavelengths to determine the distance to the place where the beam of light is pointed to. *1D* rangefinders of that kind can be used to measure the distance between a place where it is mounted on a blind user and a path. Having those measurements over time, the device can constantly check if the measurements values vary significantly in short periods of time. Thus, if a hole or imperfection of some kind occurs on the blind user path, it can be detected. A simple illustration of the *1D* laser rangefinder usage is presented in Figure 4.1.

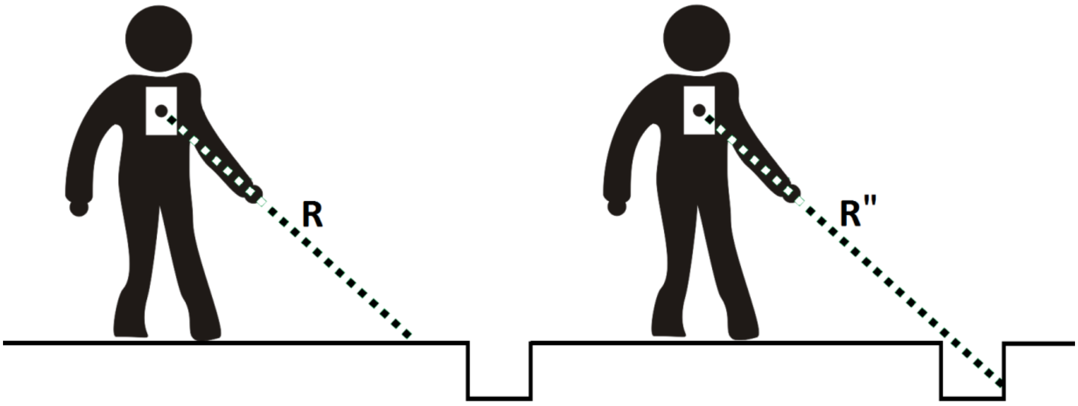

Figure 4.1. *1D LRF* based road imperfection detection example

2D laser rangefinders are commonly used with robots local orientation and human tracking systems [Cho11], [Rah11]. The graphical representation of a basic operation of a *2D* laser rangefinder is presented in Figure 4.2.

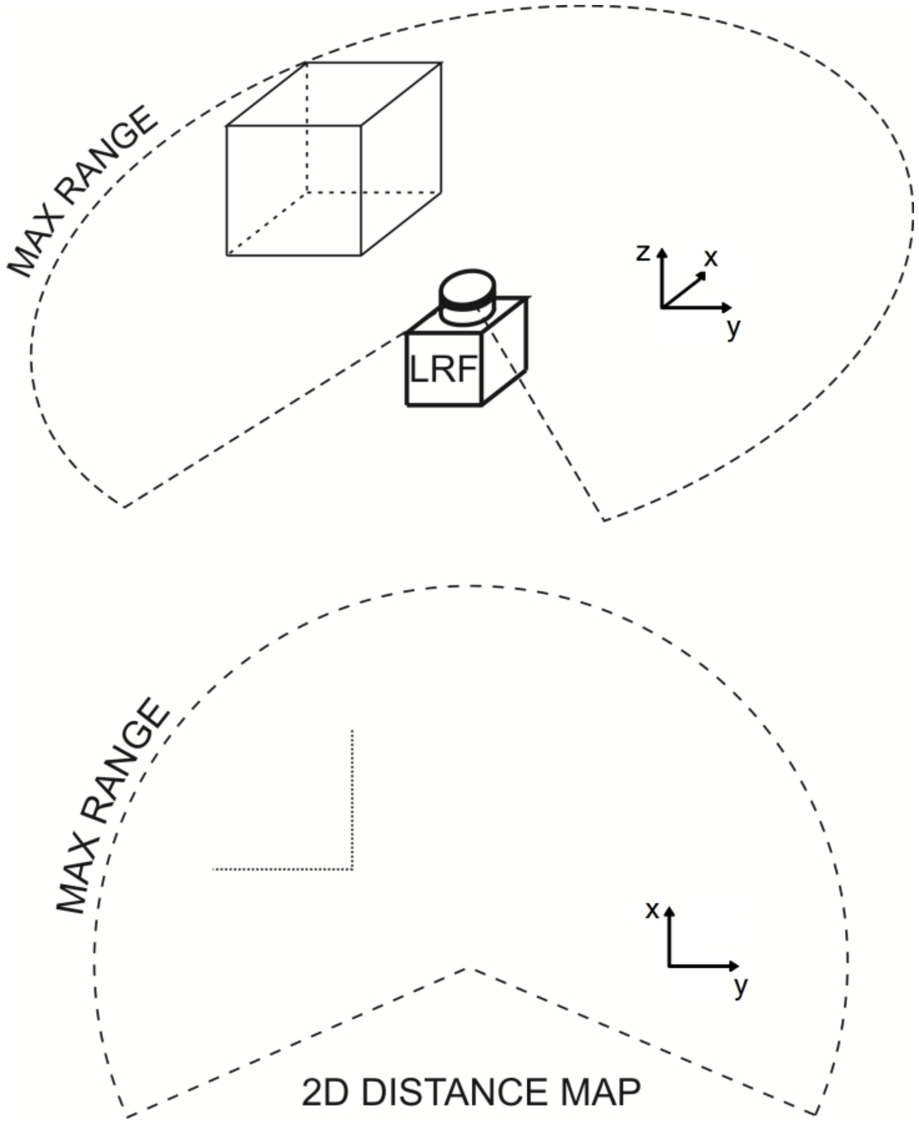

Figure 4.2. Basic operation of *2D LRF* (top) and measurement data (bottom)

The device measures distances to nearest points for each angular step in real-time. The measurements are done in a plane (*xy* plane) using a constantly moving laser beam. This gives the *2D* distance map of the specific plane in the polar coordinate system. Laser rangefinders differ in the measurement resolution, the angle of sight, the maximum range, packages, etc.

This kind of rangefinders can be used for a road imperfection detection similarly to the way that is showed in Figure 4.1. The difference is that the system measurements over time create a strip of road form and not only a line of a road form.

The visualization of sample data from both *1D* and *2D LRF* measurements is presented in Figure 4.3.

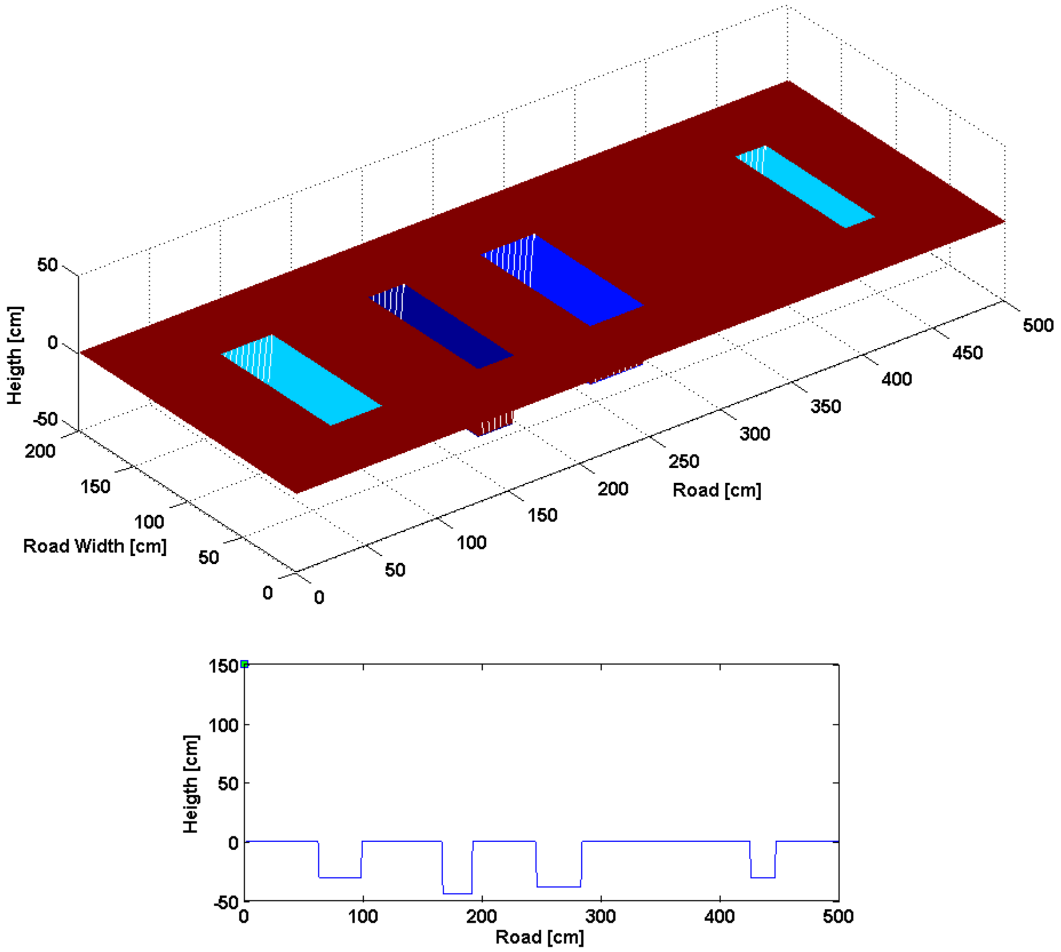

Figure 4.3. Matlab visualization of sample path measurements from *2D LRF* (top) and *1D LRF* (bottom)

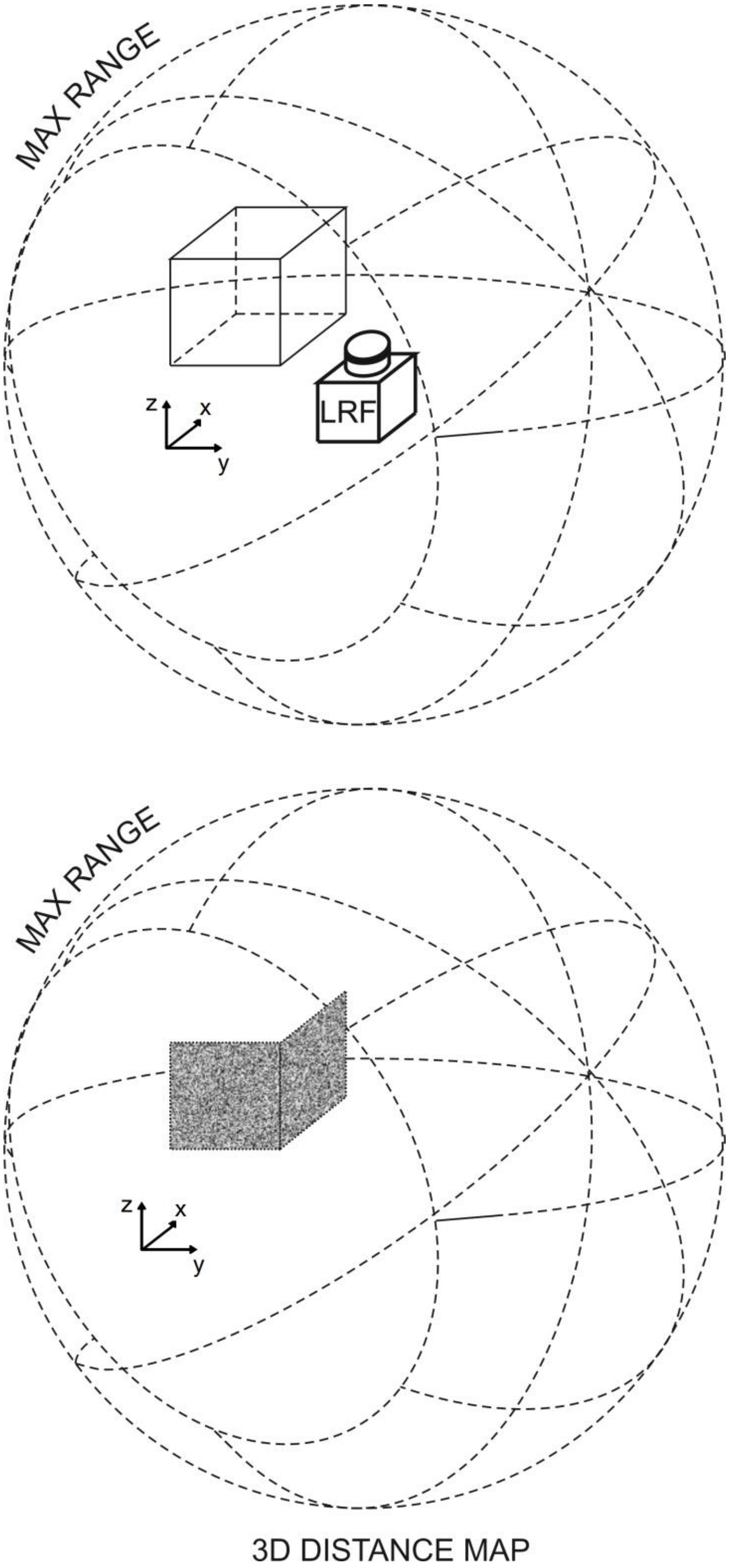

Figure 4.4. Basic operation of *3D LRF* (top) and measurement data (bottom)

To acquire a *3D* distance map the device laser beam works also in the third dimension (*z* axis). The duration of the measurement process is longer, nevertheless it makes it possible to create the *3D* distance map of a surrounding area. By having those measurements over time, the system is able to create a *3D* model of some large area and this model can also be used, among other things, for detecting road imperfections, holes and other objects for a safe navigation of blind people. The mentioned technique is also widely used in robotics for creating *3D* maps of unknown and dangerous environment, both indoors and outdoors [Hwa12], [Yok09]. The graphical representation of a basic operation of a *LRF* in a *3D* mode is illustrated in Figure 4.4.

MICROSOFT KINECT

In 2010 Microsoft released the Kinect device as an add-on to *XBOX 360* gaming console. Kinect is a commercial motion sensing input device and uses the depth sensing technology. The device is presented in Figure 4.5.

Figure 4.5. Photo of the Kinect device

Apart from its main purpose, Kinect focused attention of engineers and scientists who saw the potential in this device and possible applications based on Kinect. Therefore, Microsoft released the official *SDK* in 2012.

Kinect outputs two stream videos. One is the *RGB* video and the other is the depth level video. The sample snapshot of these two images is presented in Figure 4.6 and Figure 4.7.

The official *SDK* includes not only *API*, but also various useful tools, for instance, real time rendering tool. Sample rendering frame corresponding to scenario presented in Figure 4.6 and Figure 4.7 is shown in Figure 4.8.

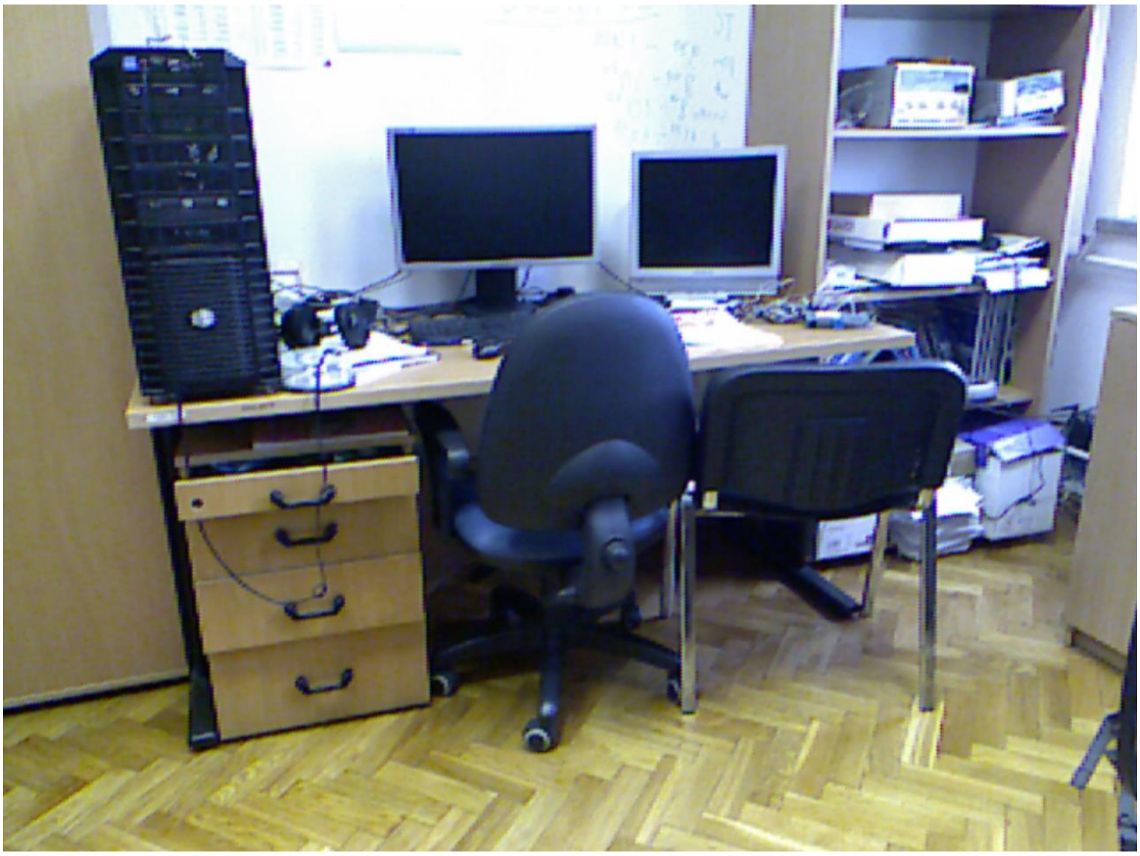

Figure 4.6. Sample snapshot from Kinect (*RGB* camera view)

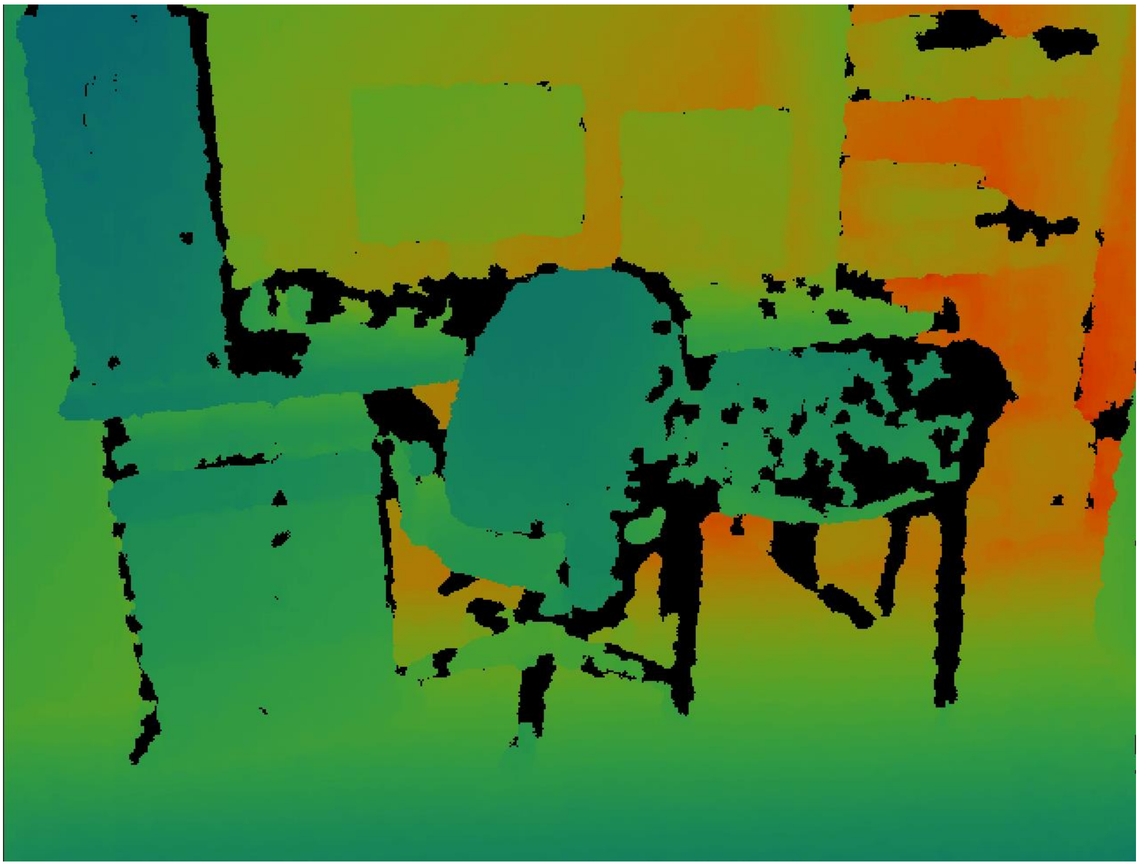

Figure 4.7. Sample snapshot from Kinect (depth sensor view in color scale)

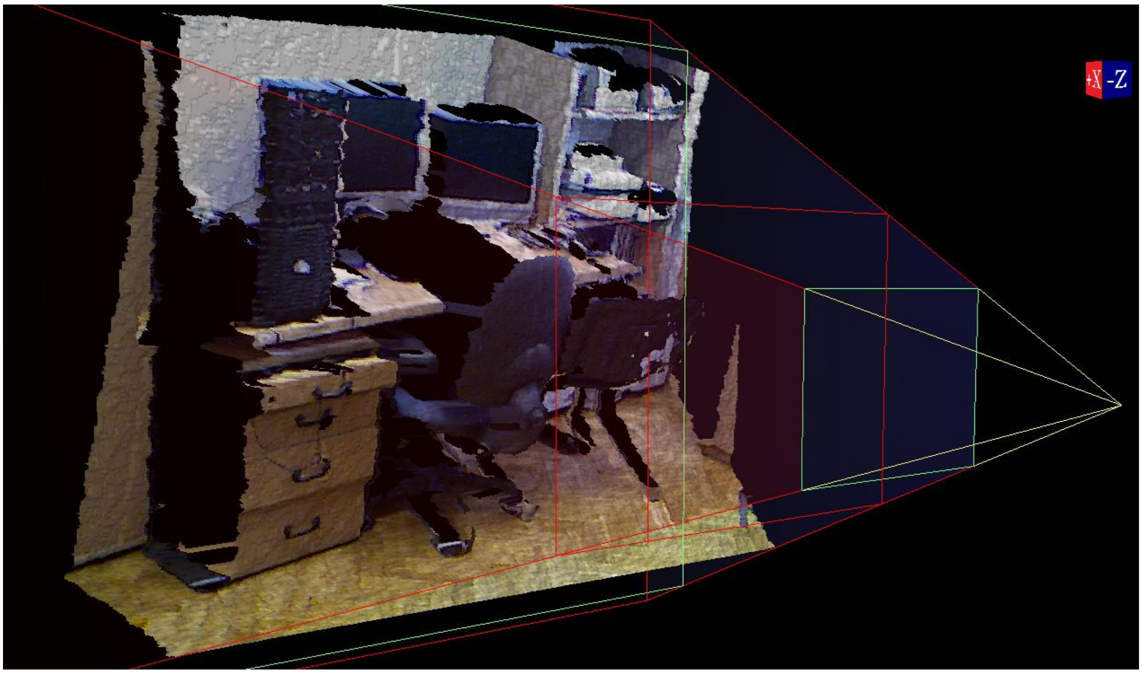

Figure 4.8. Rendering result from camera and depth sensor data

Kinect has been used in many research projects so far. Most of those applications is present in general robotics area [Ell12], human tracking [Mac12] or obstacle detection [Rak11]. Despite the fact that Kinect is relatively inexpensive as a measurement and sensing equipment, it has some major flaws, which makes it hard to implement in some sorts of applications, especially in low-power systems. Its peak current consumption is over 700 mA (5 V supply).The view angles also limit possible applications – the horizontal and vertical angular field of view is 57° and 43°, respectively.

STEREOSCOPIC IMAGING

Another method used in an object detection and recognition is stereoscopy. It has been known and studied for almost two centuries now. As many other methods in modern engineering, stereoscopy imaging is bio-inspired. Humans and many other animals perceive surroundings with a pair of eyes. The eyes capture images, but since they are shifted one from another, the images are also slightly different. These offset images are then processed by a brain in order to get additional information – depth. Based on this information, distance from recognized objects can be estimated. However, a vast group of people have problems with a depth perception.

Since stereoscopy imaging is natural for, among others, humans, it has been adopted for a computer vision. Depth is the important data for a wide variety of image processing algorithms.

Advances in electronics and optics made it possible to create low-power cameras. Mass production of cellphones, smartphones, video and digital cameras constantly allows for lowering the prices of the cameras, so they can be used practically in all systems, even low-cost ones. The significance of this impact on the world is so great that in 2009 the Nobel prize in physics was granted for creating the *CCD* sensor.

Nowadays, most stereoscopic imaging systems are based on digital cameras. They are used in surveillance and monitoring, autonomous cars, *3D* movies, object detection and recognition systems, etc. They are also being used in blind people navigation assistant systems.

There are some *EA* systems [Fer10] that uses cameras to detect and recognize some objects and signs that are significant for blind people while walking. For example pavement, zebra crossing, road signs, ads and banners, walls or barriers, etc. With help of two instead of one camera, systems are able not only to detect the mentioned objects, but to determine the distance to them. Also, there is a possibility to detect objects laying on the ground and large road excavations.

Despite all the pros of the stereoscopic imaging based systems, they are bound by some technical issues which in some situations can be perceived as major flaws [Mor09]. In order to record a good quality image stream, the ambient light has to be decent. After sunset or in shady places, without some external lamps the information from cameras is useless for processing. The external lighting, even *LED* ones, consumes additional power, thus in mobile devices larger energy bank has to be used.

Even with a good quality video feed, in order for the system to work in real-time, large computational power has to be used, therefore once again, the power consumption will be relatively high. As it was stated above, some road excavations and road holes can be detected with the stereoscopic based system. The issue is with these objects dimensions and the detection reliability. Some small road imperfections, but still large enough to make a blind person trip over, are really hard to be detected with video images due to a low diversity between the imperfections and the surroundings. Even good processing algorithms cannot provide the needed reliability.

Another important issue, commonly unfavorable for all light based systems, is the detection of glass surfaces. It can be done with complex algorithms and special camera filters, however, the reliability of detection is highly dependent on the surroundings and light intensity in the area close to the glass surfaces.

Road holes and imperfections detection system for blind people

Many consultations with blind people, their parents and teachers from the Special Educational Centre for Blind and Visually Impaired People in Kraków have shown that the process of designing electronic aid systems needs an extraordinary approach. First of all, the whole system has to be light weighted. Large additional weight can bring discomfort and if attached to the white stick, even harm i.e. a pulled muscle. Thus, also a battery should be as light weighted as possible. This leads to another, very important issue – the low power consumption and at least one day autonomous work time without need to recharge the battery. Having those two important matters on mind, the concept of the road holes and imperfections detection system for blind people was created. The approaches with a help of Kinnect or video cameras were rejected due to the need to embed high performance *CPU* for video processing, which would lead to high power consumption. The stereoscopic imaging would also be useless in dark places without some external source of light.

Ultimately, the proposed system employs *1D IR* rangefinder. This solution allows to maintain the needed functionality for holes detection and the cooperation with a low-power microcontroller makes the system mobile, relatively small and light weight. Additionally, it allows for the whole day work on one battery without the need to recharge.

IR RANGEFINDER OPERATION THEORY

The *LRFs* used for measuring long distances, in most cases utilize the time of flight principle combined with some sort of a pulse coding. However, measuring short distances with a good resolution with this method in small, portable, low-cost and low-energy systems is futile. That is why in many short range *IRRFs* the triangulation technique is being used.

The focused beam of *IR* light is being sent from *IR LED* via lens. If the beam encounters some obstacle, some part of it is being reflected and comes back to the *IRRF*. In the *IRRF* there is a small array of photodiodes and the mentioned reflected light is being combined by another lens and then it falls on some point of this array. The basic operation of the *IRRF* is presented in Figure 4.9.

The unknown distance *R* can be computed from the similarity of the triangles: *ΔABC* and *ΔDCE*. With the following equation (3).

$$R = \frac{LR'}{L'} \tag{3}$$

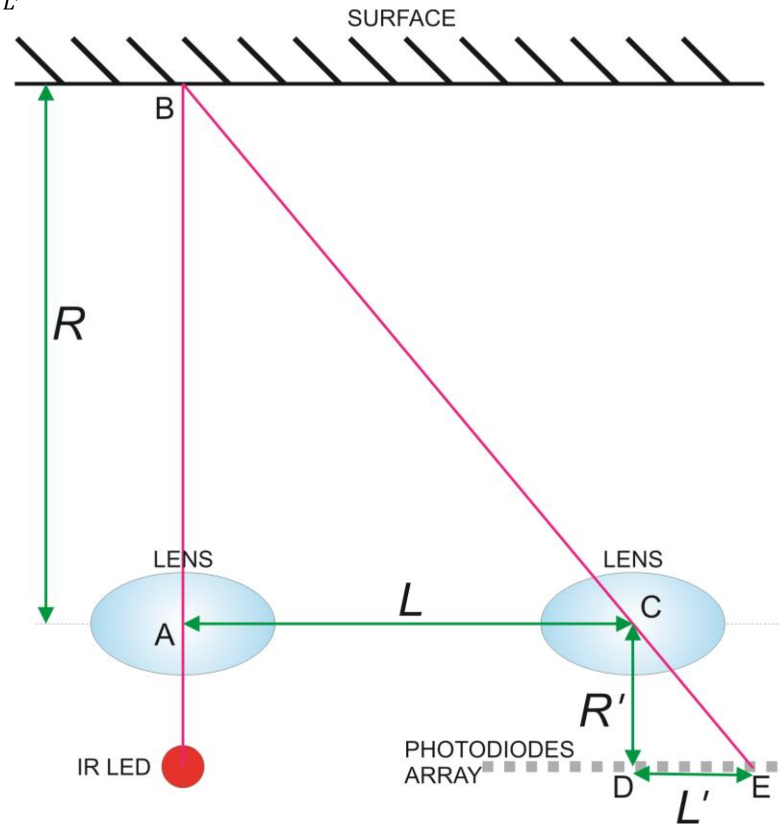

Figure 4.9. Basic operation theory of the *IRRF*

Figure 4.9 presents the basic example of light reflection only in one direction. However, in most real life cases, due to micro irregularities of the surfaces, the diffuse reflection is observed and the light is reflected into many directions. In Figure 4.9 only the light which is to cross the lens is presented and only in the simplified, one line beam. In order to combine all the reflected beams to pinpoint into the photodiode array another lens is used.

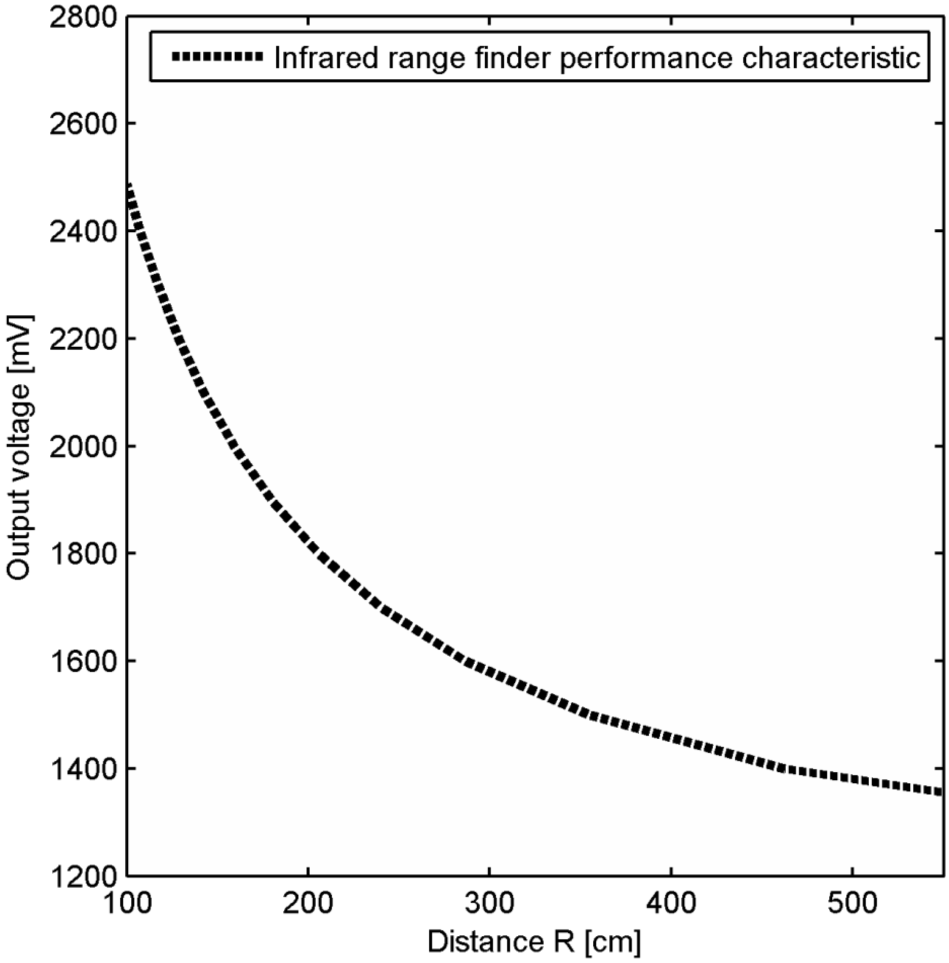

Figure 4.10. Sharp *IRRF* (*GP2Y0A710K0F*) performance characteristic

The *IRRF* used in the road holes and imperfections detection system for blind people presented in this chapter is the *1D* Sharp rangefinder – model *GP2Y0A710K0F*. It is capable to measure distances in a range from 100 cm to 550 cm. It feeds the measurements data through the analog output. The rangefinder was tested and the basic performance characteristics is presented in Figure 4.10.

PATH FORM MEASUREMENTS WHILE WALKING WITH NORMAL SPEED

Blind people walk more cautiously than people with the unimpaired vision. Therefore, in unfamiliar areas and generally outside their homes, they usually walk with normal or smaller than normal speed. The basic path form measurements presented in Figure 4.1. proved to be problematic due to the constant movement of the sensor relative to the ground. If the sensor was attached to some wheeled robot platform, all the readings from the *IRRF* would have almost the same values if only the ground was flat, without any holes. However, the mentioned user's movement causes changes in the readings. Figure 4.11 presents the *R* readings collected from 3 people who walked the flat ground. From this data it is difficult to recognize with the high probability whether the people were walking on flat ground or there were any holes or obstacles.

Depending on a walk speed and a person's movement, the *R* values deviations from the mean value vary (Figure 4.12). In most cases these deviations are not more than 10 cm. However, this is not sufficient for detecting holes that can be dangerous for blind people.

To improve the reliability of road holes and obstacles detection, some kind of stabilization is needed in order to make the measurements data usable. Since every person walks in a slightly different manner and the device should be applicable to the broad variety of users, i.e. their height, the human movements should be investigated to design proper stabilization algorithms.

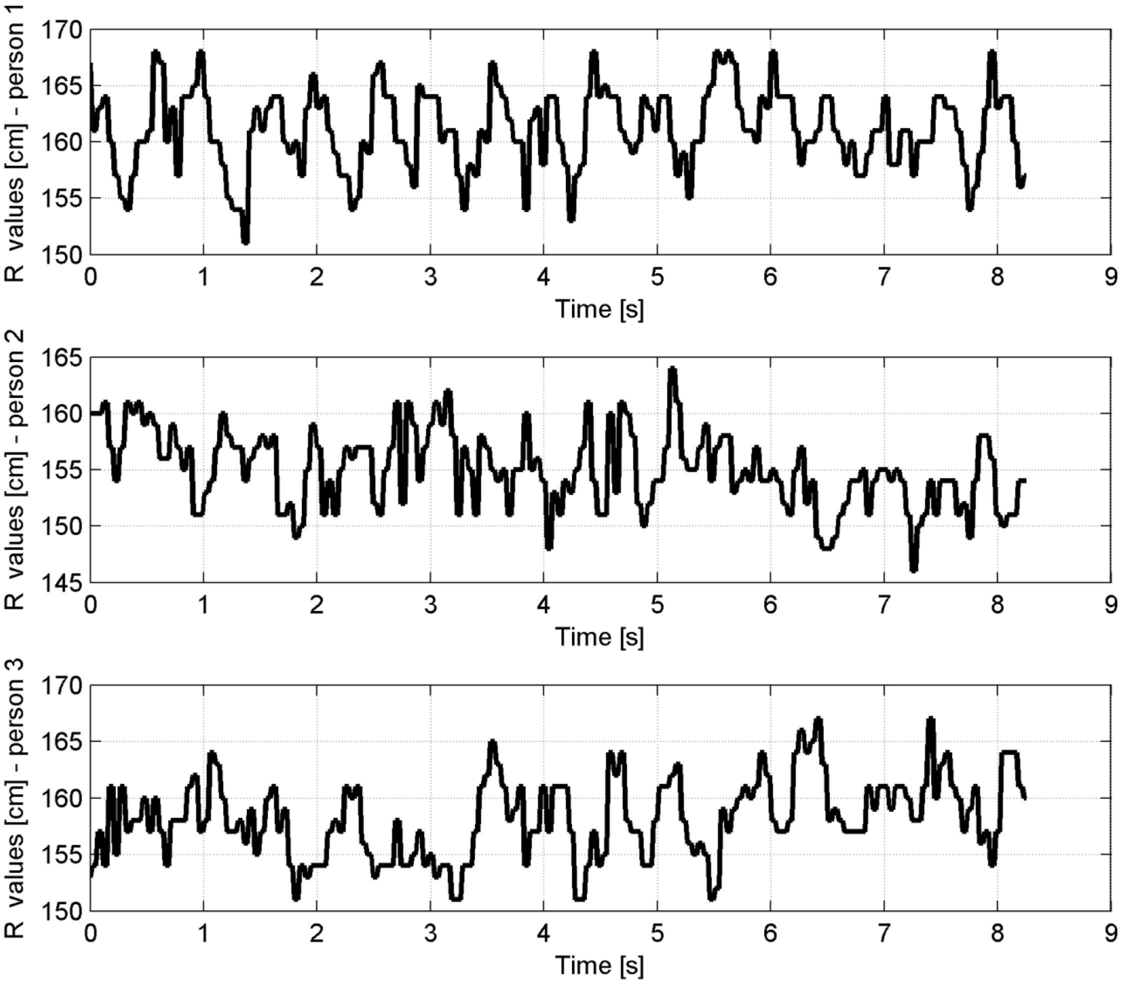

Figure 4.11. *R* readings (*IRRF*) collected from 3 people who walked the flat ground

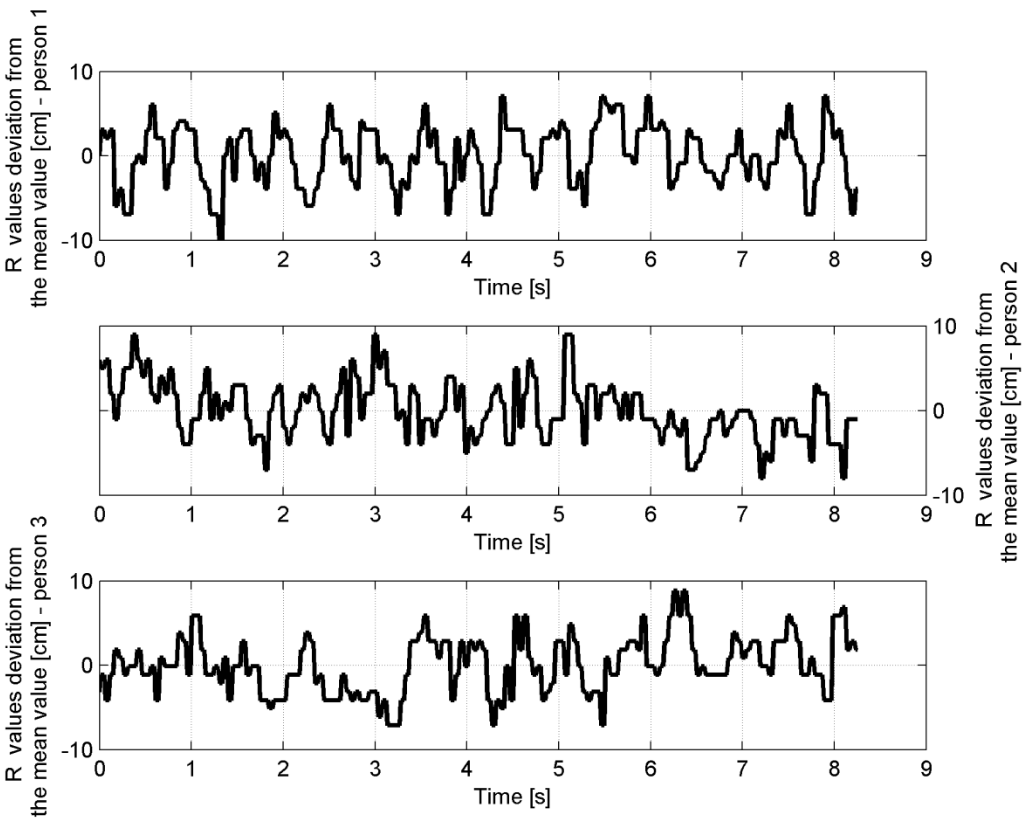

Figure 4.12. *R* values deviation from the mean value

BASIC HUMAN BODY MOVEMENT ANALYSIS DURING A WALK

The device's sensor for measuring distances will be mounted in the user's chest area. This placement is forced by the fact that during the consultations with visually impaired people, they frequently indicated that their hands should remain free (apart from carrying a white cane). Also a person's torso moves less than hands, legs or head when the person is walking.

To analyze the character and features of the *IRRF* sensor's movement, the accelerometer and the gyroscope were implemented near the sensor. Figure 4.13 presents the acceleration data from some user's steady walk. The *x*, *y* and *z* axes are consistent with the world frame format, thus *y* is the walking direction, *x* is the lateral direction and *z* is the vertical direction to the walking direction. This could be accomplished with the gyroscope data.

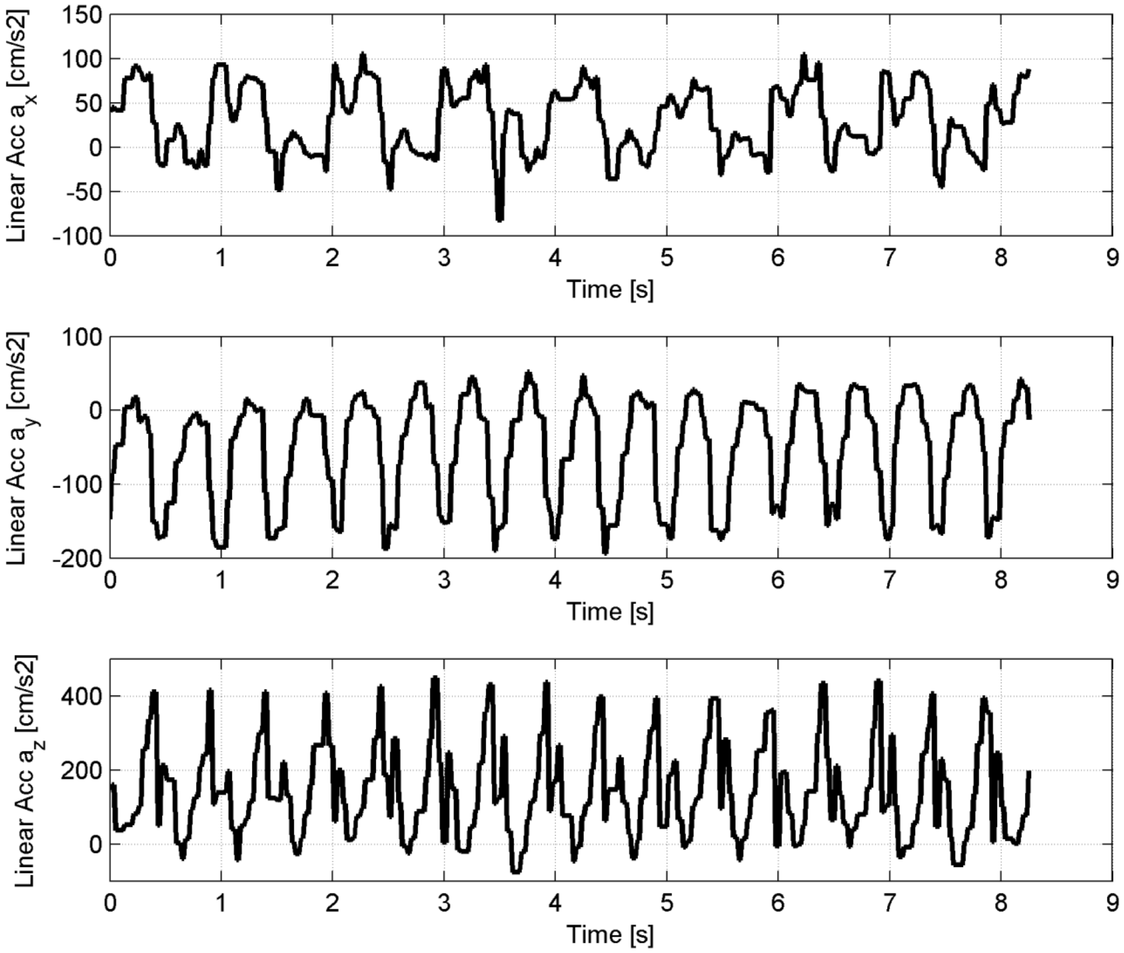

Figure 4.13. Linear acceleration data from a steady walk (in world formal)

For better understanding the magnitudes of the accelerations data, the plot of the deviation from the mean value is presented in Figure 4.14.

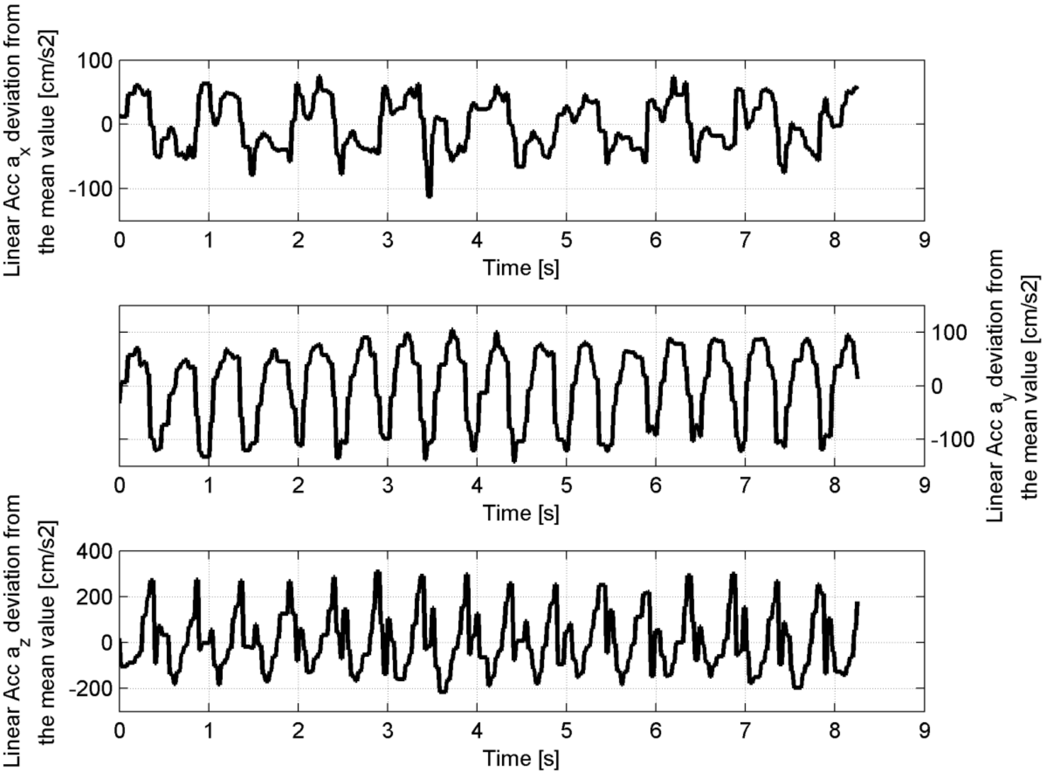

Figure 4.14. Linear acceleration deviation from the mean value

The amplitudes of accelerations vary, depends on the user and type of walk. So, it would be difficult to design a stabilization algorithm based only on those amplitudes. Nevertheless, all axis acceleration plots are quasi-periodic, but *z* displacements influence the *R* measurements the most. Figure 4.15 presents the frequency spectrum of the *z* axis accelerations.

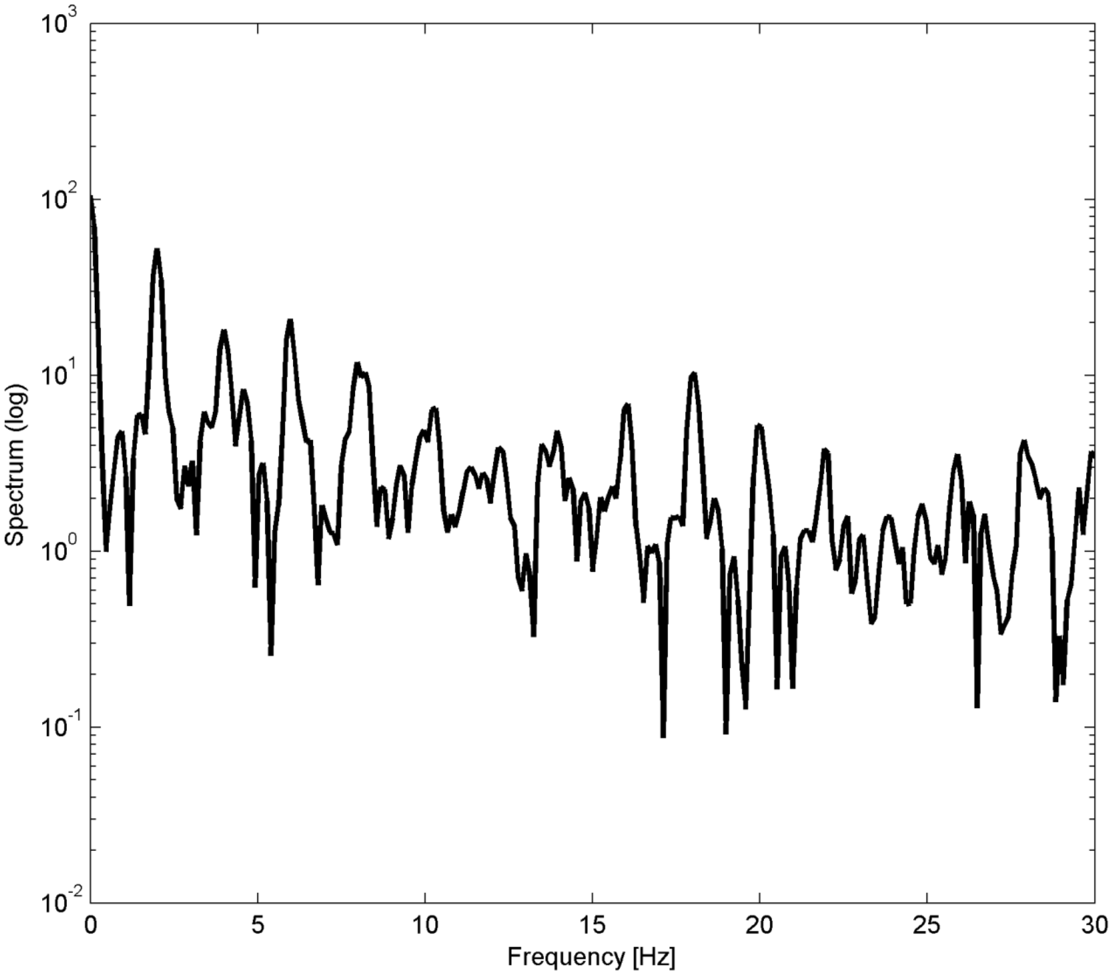

Figure 4.15. Frequency spectrum of the *z* axis accelerations

Some feature of the user's movement has to be found in order to filter measurements data from the *IRRF*. This property has to be ubiquitous in a vast majority of people walk patterns.

DEAD RECKONING

One of the ways to obtain the change of position is a dead reckoning method. This method was often used in navigation on sea before the *GPS* was operational and position of the sun on the sky could not be established. Basically, by having a known, fix position and in addition course and speed, one can calculate a current position after a certain period of time. This position becomes the alleged, actual position and the next position can be calculated after another period of time as a next step.

In theory the algorithm should give the real position. However, on sea some conditions can cause errors in calculations, for instance, wind. It that way, the error from one step propagates to all the following steps. Thus, this method not only accumulates errors from every step, but also propagates them and introduces errors to the computed position that is being taken for another calculation as a real position.

The dead reckoning technique is also used for inertial navigation with electronic accelerometers, compasses and gyroscopes. By having linear acceleration, direction and angular velocity data from the mentioned devices, one can track a position and orientation of the device. The progress in micro-machined electromechanical systems (*MEMS*) technology made possible to design small, low cost and light weighted inertial measurement units (*IMU*). They become the integral parts of almost every smartphone or tablet.

MEMS accelerometers and gyroscopes are subjects for errors [Tsa08]. Bias error is a constant error which causes the output to give some non-zero value, despite that, for example there is no acceleration. The output signal suffers also errors from temperature effects and white noise. Calibration errors and bias instability create measurements drift which is very undesirable while computing the change in position as a double integral from acceleration.

Some techniques and algorithms can be used to minimize these errors. Nevertheless, inertial navigation without any external signals cannot substitute global navigation systems like *GPS* or *GLONASS*. Although, there are hybrid systems which utilize *IMU* to navigate for short periods of time when satellite signal cannot be received (for instance in tunnels) or to improve accuracy of satellite position fix in urban areas [Bar10b].

There are some operational solutions to track the body movement and record the displacement with a high accuracy. One of those solutions is presented in [Mad11]. The author created hardware and designed algorithm to obtain a foot *3D* position in time. By calibrating the *IMU* and using the moments when the foot is fully placed on the ground, thus the speed is zero (the acceleration is also zero in all axes, excluding acceleration due to gravity), the algorithm can safely zero the calculated speed and start double integrating when the foot moves again. In this way, the author gets rid of the long term drift caused by the accelerometer and minimizes errors accumulation. Figure 4.16 presents the device to track foot movements and the displacement data plot from the algorithm.

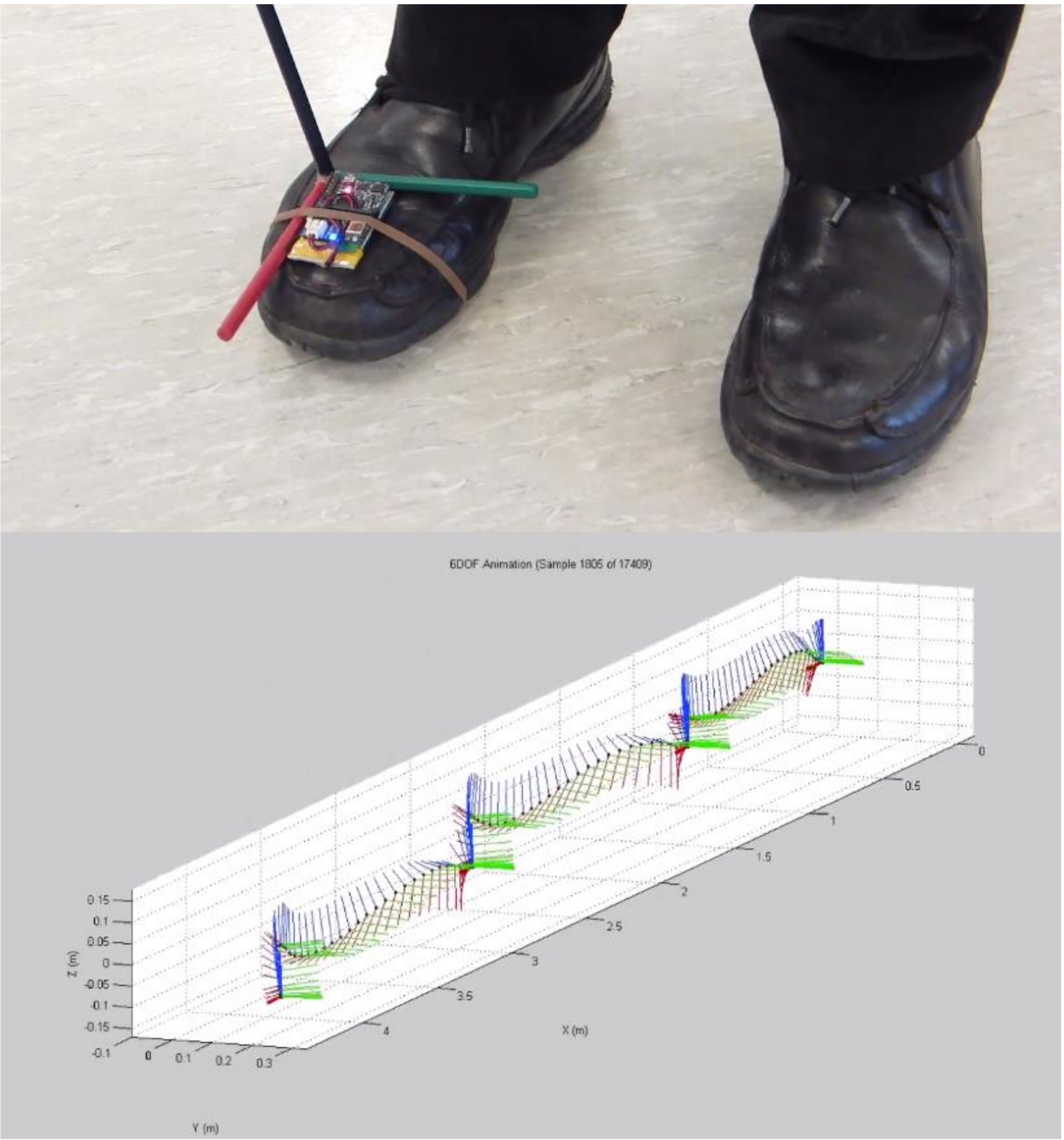

Figure 4.16. Foot tracking system [Mad11]

Tracking displacement of any human body part requires different approach in order to minimize errors. Since the hole detection device is to be placed onto the chest area, algorithms for tracking arms or legs are ineffective. Although, in a long period of time the displacement of the whole body would be the same in a macro scale, a specific algorithm has to be implemented in order to stabilize the *IRRF* measurements.

ZERO VELOCITY POINTS (*ZVP*)

Excluding people with some movement disorders, the way that people walk can be analyzed as the *3D* displacement in time. As it is stated in the previous section, the z axis movement strongly affects the *R* measurements. This movement can be presented as some sinusoidal plot, both amplitude and frequency modulated, depending on the characteristics of the walk. The data from the plot presents displacements of the sensor, thus it should be used in the stabilization algorithm. However, it is difficult to obtain the displacement of the user in *z* axis in the continuous walk. Even having the acceleration data and integrating it twice, it gives the displacement data with the sum of two constants from integration process and a drift. Thus, this method is not proper to design the algorithm for obtaining correct *R* measurements.

A people's walk analysis has shown that there are usually two moments for every two steps where velocity in z axis (v_z) equals 0 – that is when a person is at the highest and lowest *z*-level – and the difference between these *z*-levels is similar in a steady walk. These zero velocity points (*ZVP*) can be used for the *R* measurements stabilization.

The velocity in z axis (v_z) can be calculated from the z axis acceleration data (a_z). The acceleration is a change in the velocity over time.

$$a_z = \frac{\mathrm{d}v_z}{\mathrm{dt}} \tag{4}$$

Since the acceleration data is delivered with the accelerometer, the velocity can be calculated with (5).

$$v_z = \int a_z \mathrm{dt} \tag{5}$$

The acceleration data (a) is presented in Figure 4.13. The integration can be calculated as the area under the curve (or over where the function values are below zero). There are many algorithms to calculate this. One is to use the trapezoidal method.

The acceleration samples are being delivered from the accelerometer with the sample period Δt. Therefore, the integral can be calculated with (6)

$$v_z = \int_{\mathrm{a}}^{\mathrm{b}} a_z \mathrm{dt} = \lim_{\mathrm{n}\to\infty} \sum_{\mathrm{i}=1}^{\mathrm{n}} a_z[i] \cdot \Delta t \tag{6}$$

where $\Delta t = \frac{b-a}{n}$. Thus, using the trapezoid area formula and taking into consideration that the acceleration function can be either ascending or descending, the velocity in *z* axis (v_z) can be calculated from the *z* axis acceleration data (a_z) with (7), where *i* is an integer sample number ($i \geq 0$).

$$v_z[i+1] = v_z[i] + \left(a_z[i] + \left|\frac{a_z[i+1]-a_z[i]}{2}\right|\right) \cdot \Delta t \tag{7}$$

The trapezoidal method is used to numerically calculate the velocity from acceleration samples to reduce errors of integration. The samples are acquired with the Δt period. Since, some moments can occur between steps that have accelerations equal zero, but still the user is in motion (speed is not zero), thus every velocity is calculated as the change from the previous velocity.

The velocity in *z* axis (v_z) calculated from the *z* axis acceleration data (a_z) presented in Figure 4.13 and the frequency spectrum of the velocity, is given in Figure 4.17. This data also contains the accelerometer and gyroscope error and drift.

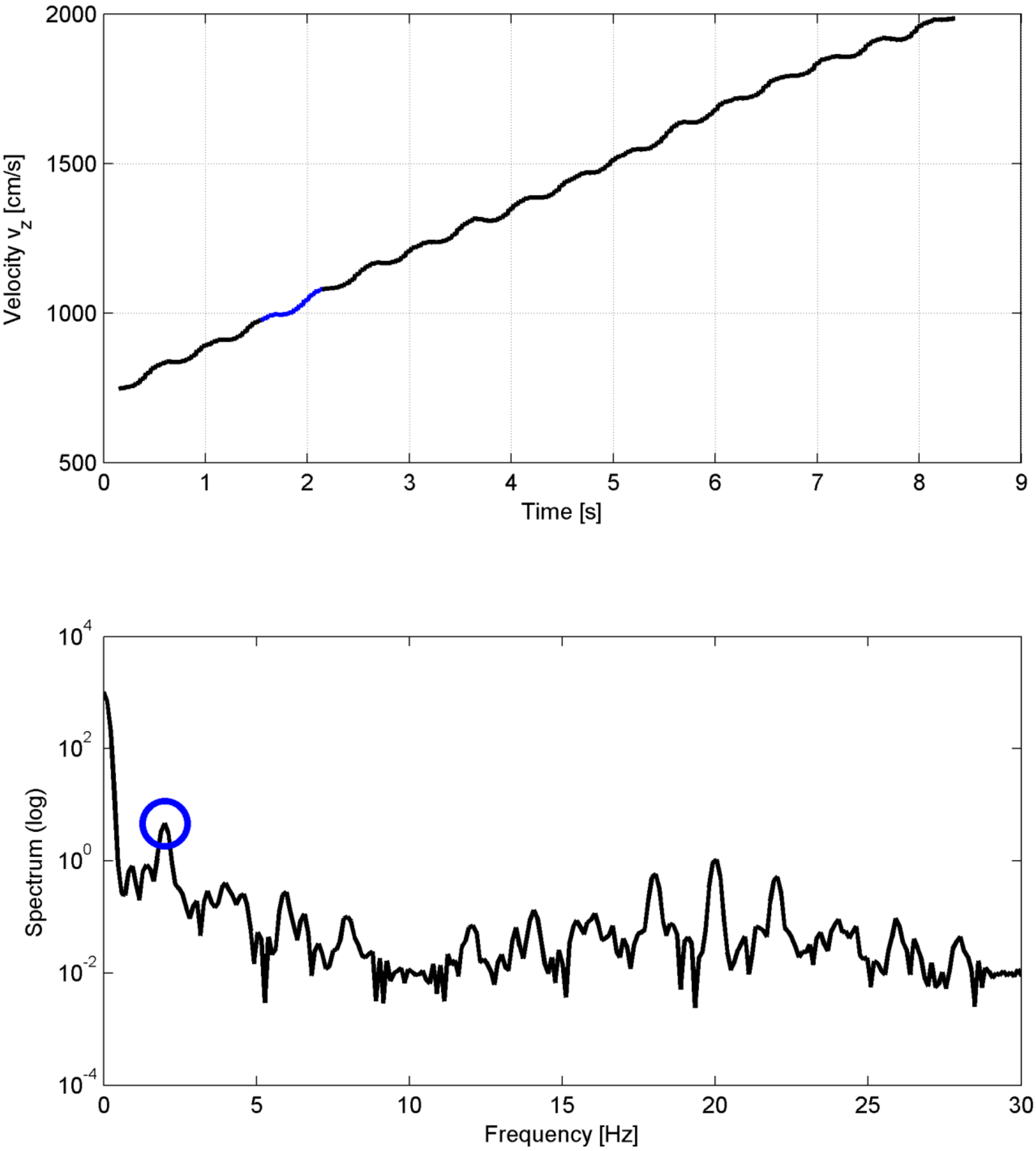

Figure 4.17. Velocity in *z* axis data and its frequency spectrum (with errors and drift)

As it is observed in Figure 4.17, the velocity has a *DC* constant which is being multiplied in every computation. To obtain the clear *AC* plot, the *DC* constant can be determined in a simple calibration process when the device is not moving. Subsequently, the constant should be subtracted in every velocity calculation. However, this constant can and most likely will drift and slightly change its value. That is why, the better solution is to use a digital filter.

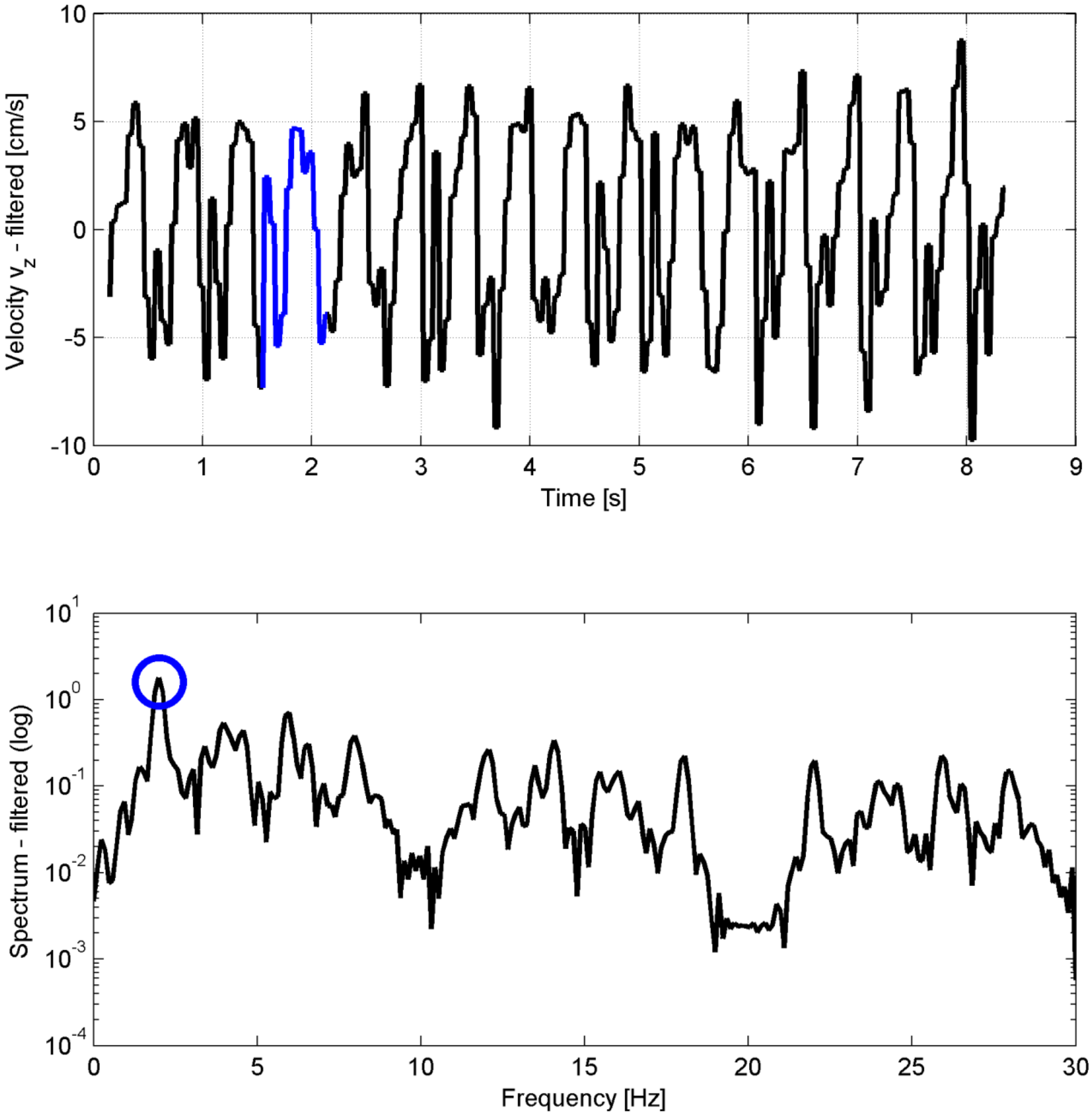

Figure 4.18. Velocity in *z* axis data and its frequency spectrum after filtration

The velocity v_z is a characteristic, periodical signal, therefore it can be filtered to obtain clear velocity signal in which *ZVP* are possible to be detected. In Figure 4.17, period of this signal and its corresponding frequency spike in spectrum are marked (blue color). The signal and its spectrum after filtration by (8) are presented in Figure 4.18.

$$v_{z\,FILTERED}[\mathrm{i}] = v_z[i] * h_1[i] * h_2[i] \qquad (8)$$

where $H_1[z] = (z^{-1} - z^{-2}) \cdot (z^{-1} - z^{-2})$

and $H_2[z] = (z^{-1} + z^{-2} + z^{-3}) \cdot (z^{-1} + z^{-2} + z^{-3})$.

The $v_{z\,FILTERED}$ data reduces the measurement drift errors which come from electronic accelerometers in a way that the zero velocity points can be detected. This is the key point to the stabilization algorithm.

IRRF MEASUREMENTS 2-STAGE STABILIZATION USING ACCELEROMETER AND GYROSCOPE DATA BASED ON KALMAN FILTER

As it was mentioned in the previous section, the measurements from *IRRF* have to be filtered in order to get the stabilized readings. The device, thus the sensor, is placed in the user's torso area. Therefore, when the user is walking, the sensor is not only constantly changing its position in z axis, but also the angular position of the *IRRF* focused beam changes. This angle can be described as the angle between the beam and the normal to the ground. This angular displacement is present when the user is moving and also can be present when the user is standing still, due to the movement of the chest area while breathing. Figure 4.19 illustrates the described angle.

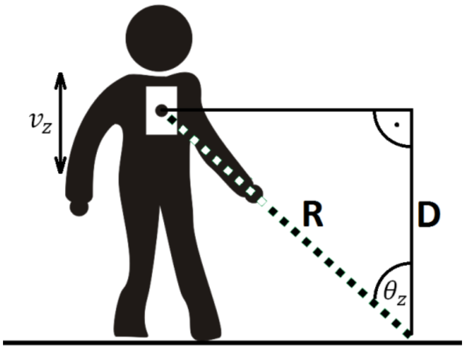

Figure 4.19. Variable angle between *IRRF* beam and normal to the ground

Employing Kalman filtering for the accelerometer and gyroscope data makes it possible to calculate the angle θ_z in real-time [Bis01]. The state in a linear system can be described with (9).

$$x[i] = Fx[i-1] + Bu[i] + w[i] \tag{9}$$

where:

$x[i] = \begin{bmatrix} \theta_z \\ \dot{\theta}_b \end{bmatrix}$

$\dot{\theta}_b$ – the angle bias (a gyroscope drift), based on both a gyroscope and accelerometer data,

$F = \begin{bmatrix} 1 & -\Delta t \\ 0 & 1 \end{bmatrix}$ – the state transition model,

$B = \begin{bmatrix} \Delta t \\ 0 \end{bmatrix}$ – the control model,

$u[i]$ – the control input (a gyroscope measurement $\dot{\theta}_z[i]$),

$w[i]$ – the process noise (Gaussian distributed with a zero mean, with a covariance $Q[i]$),

$w[i] \sim N(0, Q[i])$,

$Q[i] = \begin{bmatrix} \mathrm{Q}_\theta & 0 \\ 0 & \mathrm{Q}_{\dot{\theta}_b} \end{bmatrix} \Delta t$ – the estimate of the bias and the accelerometer are independent (both Q_θ and $\mathrm{Q}_{\dot{\theta}_b}$ are constants).

In this filter the data from accelerometer is converted to the measurement in (10).

$$z[i] = Hx[i] + p[i] \tag{10}$$

where:

$H = [1 \quad 0]$ – the observation model,

$p[i]$ – the measurement noise (Gaussian distributed with a zero mean, with a covariance M),

$p[i] \sim N(0, M)$.

Since there is only one measurement source, the covariance of the same variable is the same as the variance. If this variance is large the filter will respond slowly, because it will trust the measurement less.

The Kalman filter consists of two phases: the prediction and the update. The first stage is to predict the current state (11) and the error covariance matrix (12) based on the previous states, the previous error covariance matrices and the gyroscope measurements.

$$\hat{x}[i|i-1] = F\hat{x}[i-1|i-1] + B\dot{\theta}_z[i] \tag{11}$$

$$P[i|i-1] = FP[i-1|i-1]F^T + \mathrm{Q}[i] \tag{12}$$

These estimations are called *a priori*. The error covariance matrix estimates the trust value of the (11). The lower the value, the greater the trust.

The second stage is to update the estimation. The innovation – the difference between the measurement $z[i]$ and the state in (11) – is calculated in (13).

$$\tilde{y}[i] = z[i] - H\hat{x}[i|i-1] \tag{13}$$

Then, the innovation covariance is calculated in (14).

$$S[i] = HP[i|i-1]H^T + \mathrm{M} \tag{14}$$

The innovation covariance matrix estimates the trust value of the measurement based on (12) and *M*. The lower the value, the greater the trust.

The last step necessary for the update stage is to calculate the Kalman gain (15).

$$K[i] = P[i|i-1]H^T S^{-1}[i] \tag{15}$$

The Kalman gain shows if the innovation can be trusted. The update calculation is presented in (16) and (17). This estimation is called *a posteriori*.

$$\hat{x}[i|i] = \hat{x}[i|i-1] + K[i]\tilde{y}[i] \tag{16}$$

$$P[i|i] = (I' - K[i]H)P[i|i-1] \tag{17}$$

where *I'* is the identity matrix.

Having the angle θ_z, is useful to obtain the *D* values with equation (18).

$$D[i] = R[i] \cdot cos(\theta_z[i]) \tag{18}$$

The *D* values represent the distance between the sensor and the ground (height). Assuming that the displacement in *z* axis is zero, this distance should remain constant when a blind user is moving and no holes are present. When the *IRRF* focused beam spots the hole, the distance *D* increases its value. This rapid change indicates that the hole of some kind is in front of the user. This is the first stage of the range sensor stabilization – the angle stabilization.

Figure 4.20 presents the *D* values as the *R* measurements stabilization results from one person in Figure 4.11.

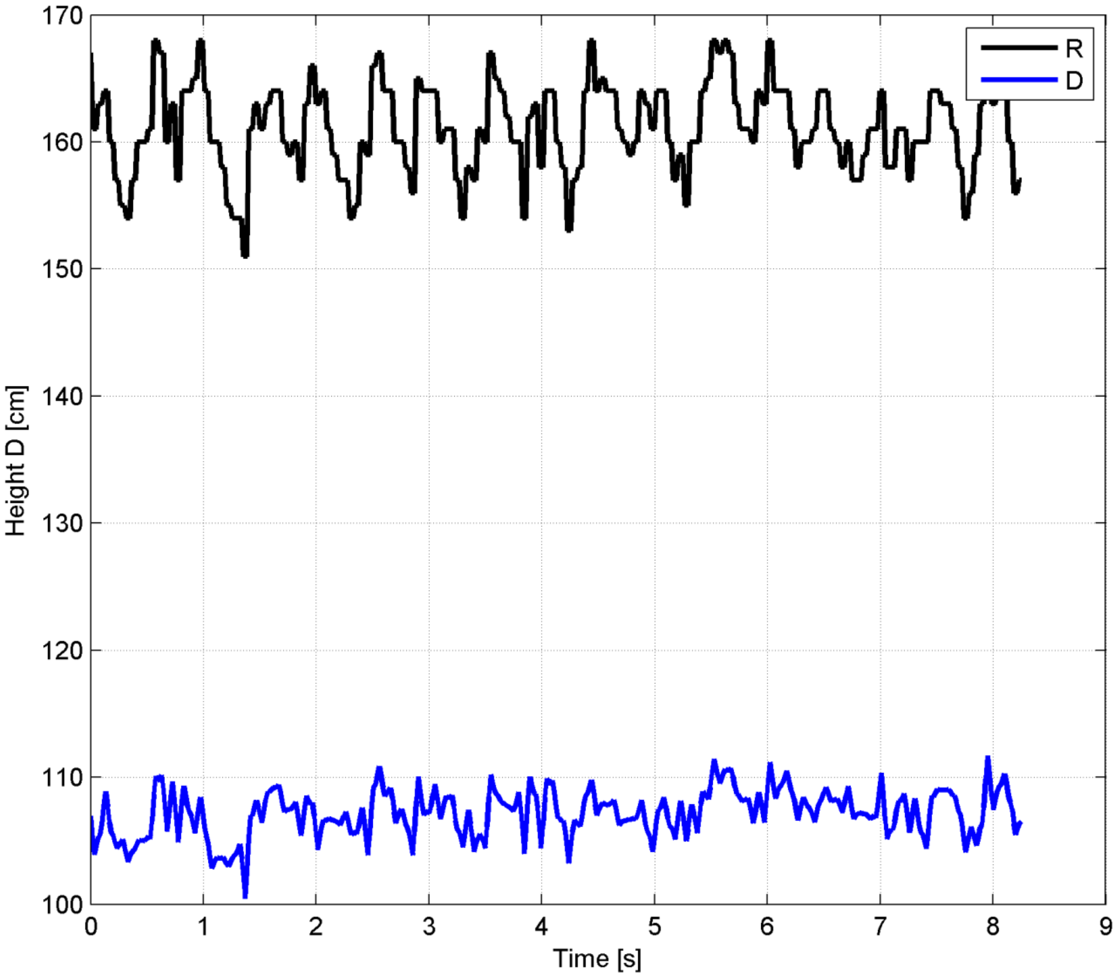

Figure 4.20. *D* values as the *R* measurements stabilization results

Figure 4.20 shows that the *D* values do not present the constant value, although the user is walking the straight ground. The angle stabilization significantly decreased the deviation from the mean value, however for the device to be able to detect small holes with high reliability, the *D* values have to be more stable. Therefore, another stage of stabilization is needed, due to non-zero displacement values in the *z* axis when the blind person is walking.

The method described in the previous section to detect the moments when the velocity in *z* axis equals zero, can be used as the second stage of the range sensor stabilization – the *ZVP* stabilization. Since the difference between *z*-levels is similar in a steady walk in zero velocity points, so the mean value from the *D* values computed in these points time is also similar, thus almost constant. When no motion in *z* axis is detected, then only the angle stabilization is active.

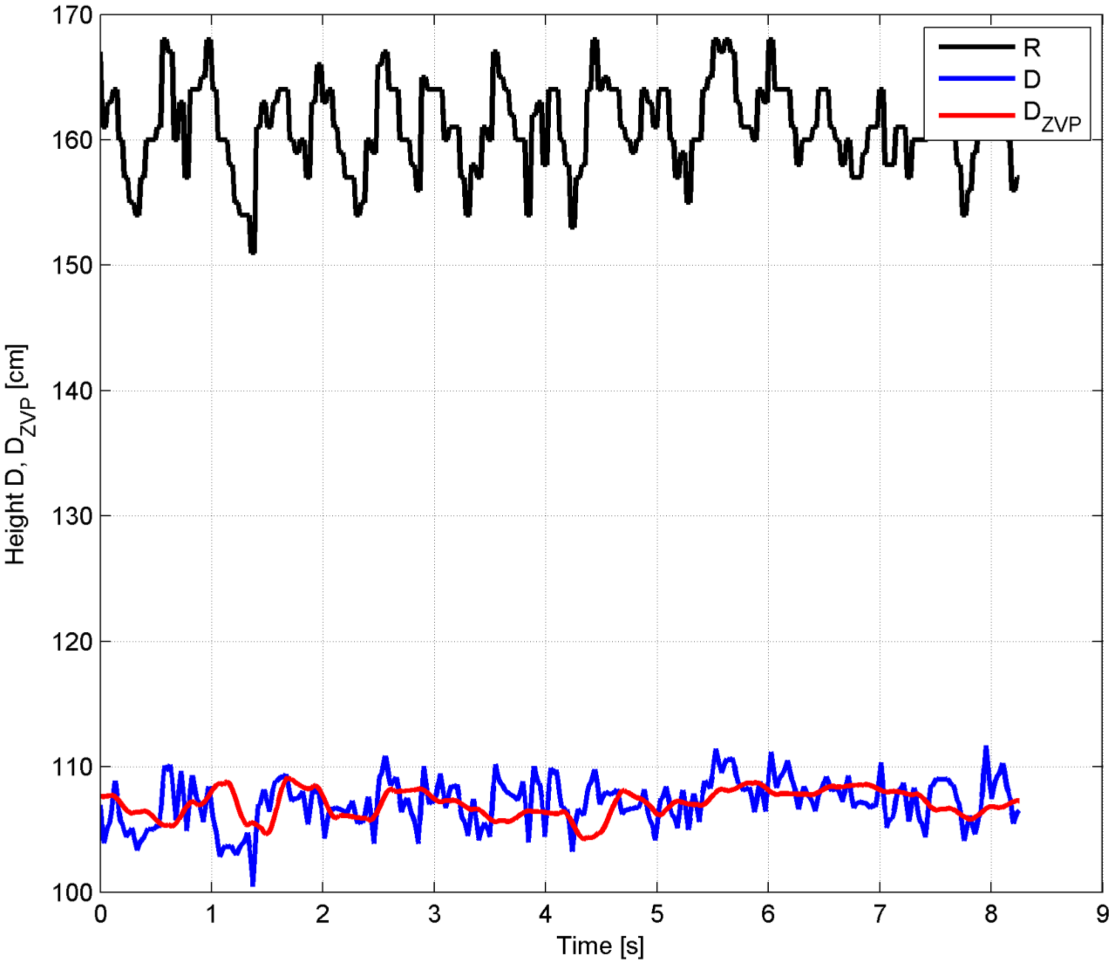

Figure 4.21. Sample 2-stage stabilization data

Figure 4.21 presents the two stabilization stages of the *R* measurements from the *IRRF* (D_{ZVP}). This shows that the proposed two stages stabilization algorithm is operational and deals with both the angle changes and *z* axis displacements when the user is walking. The main advantage of this algorithms being implemented in the electronic assistant device is that it can be used by the wide group of blind people. The algorithm deals with the variety of users' movements, user's dimensions and what is also important it does not need much computational power, thus it can be used in low-power devices that runs on small batteries.

Besides the main functionality, which is stabilization of the measurements, the algorithm has to meet a 'real-time constraint', thus the time from the hole occurrence to the moment when the device can detect this hole with the high reliability has to be short enough, so the user still has sufficient time to react accordingly. The delays caused by the filtration of readings from *ZVP* and also by data computations have to meet the real-time criteria. More extensive tests descriptions and scenarios are presented in another section of this dissertation. Nevertheless, in order to maintain the continuity of thought, a simple 6 cm hole detection data (when a blind person is moving slowly) is presented in Figure 4.22.

The time between the occurrence of the hole and the moment when the filtered height changes by the value of this hole is only a little over than 0,2 s. It gives the user enough time to react when the user is walking the normal pace, since the *IRRF* beam is by default set to check the area more than 1,5 m in front of the user.

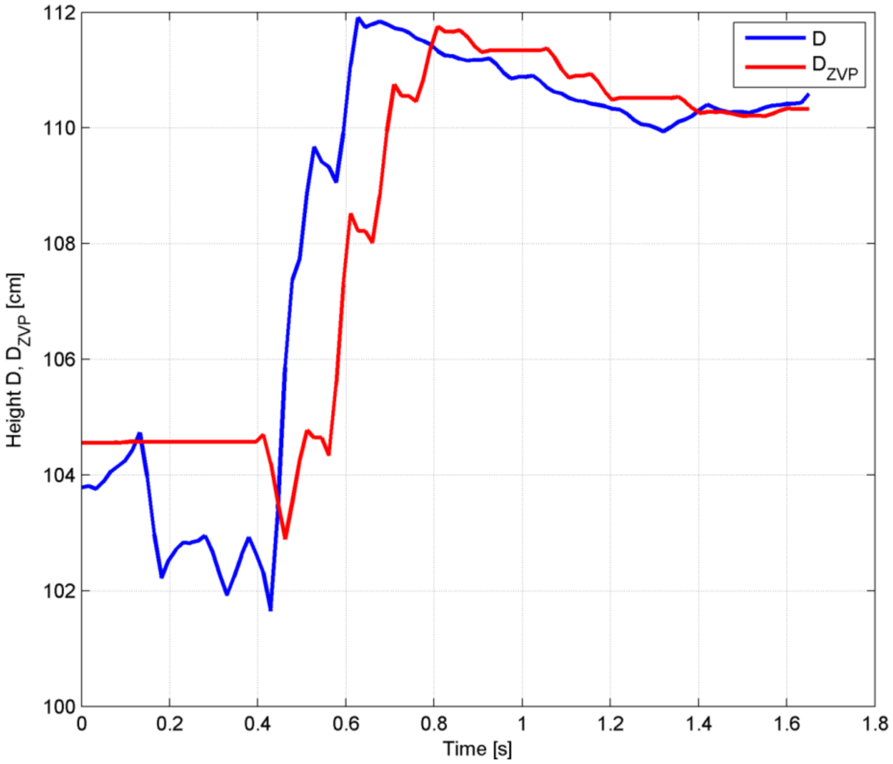

Figure 4.22. Filtration data in a scenario of detection 6 cm hole

CHAPTER 5: DETECTING HEAD LEVEL OBSTACLES

Nowadays, almost every blind person uses some kind of a white stick. Due to the fact that blind person's remaining senses simply cannot compensate for the lack of vision, a white stick has become an integral part of every blind person's life. In some special educational centers for visually impaired children, like the one in Kraków, children are taught how to use a white stick to detect and avoid obstacles. Despite the fact that blind people are very skilled in using white sticks, this aid is not sufficient enough to ensure a high safety level when a blind person is walking, especially in unknown areas. Many consultations with visually impaired people have showed that besides road imperfects, for instance, holes, bumps, etc., other obstacles which occur on a level of a head are very dangerous and not so easy to detect only with a help of a white stick. Additionally, visually impaired people are able to detect obstacles which occur from their waist to the ground, only with a help of a white stick. However, some obstacles require remote distance measurements due to the fact that a close encounter with the obstacles could harm the blind person.

Some solutions utilizing laser range finders and other devices, for example like the Kinect, are presented in CHAPTER 4. Laser range finders due to their physical restrictions have problems detecting glass surfaces. Furthermore, laser range finders consume too much power to be employed for a whole day performance in the battery-supplied mobile systems which are used by people. That is why the amount of time for which the *3D* laser scanner is to be turned on should be reasonable. Therefore, an ultrasound range finder can be implemented instead of the laser scanner, to detect obstacles in front of a blind person.

This chapter presents a multichannel ultrasonic range finder designed and developed for the *MOBIAN* project. Thanks to a simple-to-manage-by-any-microcontroller interface this ultrasound driver can be used not only in blind people navigation systems, but also as replacement in some mobile robots surrounding perception systems [Kov07] and low-cost industry distance measurement systems [Mis11], etc. The main functions of this subsystem is to scan the environment, detect and recognize obstacles, calculate their distances to the blind person and inform, if necessary, about the danger.

Ultrasonic transducers possibilities

Many materials are subjected to a piezoelectric effect, both synthetic ones like langasite (crystal), barium titanate (ceramics) and natural ones like quartz, topaz, *DNA* and even wood. The piezoelectric effect creates an electrical field when materials strain. This happens due to a change in an electric charge density caused by the material stress. There are many applications of those materials: sensors, voltage generators (including energy harvesting transducers), spark generators, medical devices, etc. The piezoelectric effect works both ways, which means that by applying an electric field, a mechanical movement is generated.

Piezoelectric materials are used for manufacturing membranes for ultrasonic transducers. A single ultrasonic transducer embeds piezoelectric membrane, which when excited, creates ultrasonic wave that propagates throughout the environment. Reversing the process – when a frequency compatible wave meets the membrane, it creates electric signal that can be detected and processed. These types of transducers, despite their simplicity and low price on the market, have wide application possibilities and are used for distance measurements in many complex systems.

It is important to know detection capabilities of a single transducer object. They are limited by a sound wave propagation and reflection theory [Res10]. For object detection purposes the most important aspects of ultrasonic transducers are how small objects can be detectable, object's surface position and sensor's directionality. Figure 5.1 presents the directionality characteristic of a simple 40 kHz ultrasonic transducer.

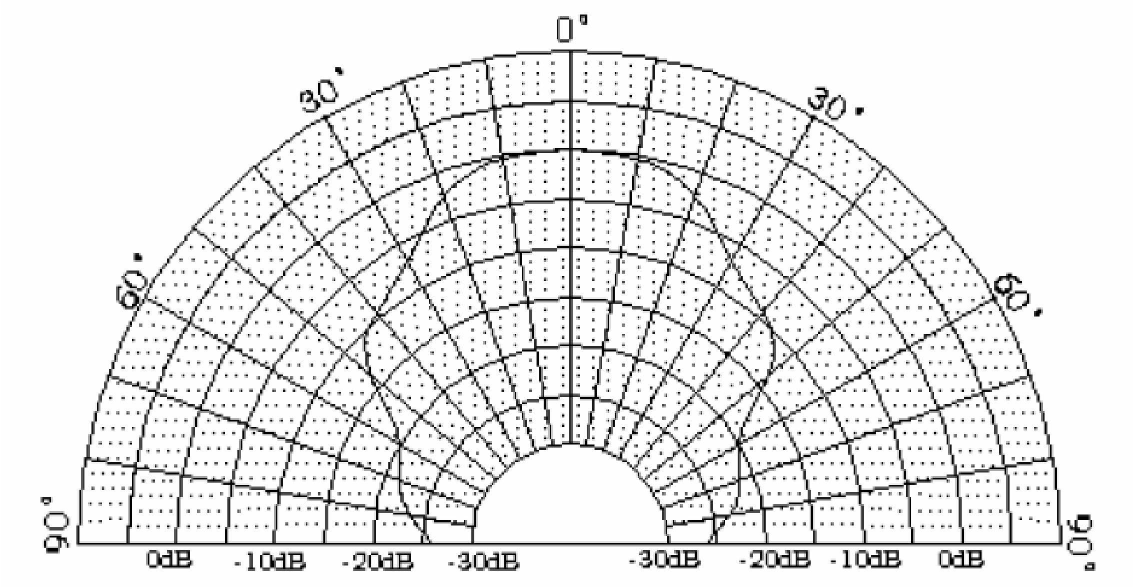

Figure 5.1. Directionality characteristic of a simple 40 kHz ultrasonic transmitter

The capabilities were tested using small, square shaped pieces of places. All the results were normalized to the results from the largest plate. The test system is presented in Figure 5.2. The microcontroller excites the ultrasonic transmitter (*T*). When the reflected wave meets the receiver (*R*), the signal is amplified and reads with *ADC*.

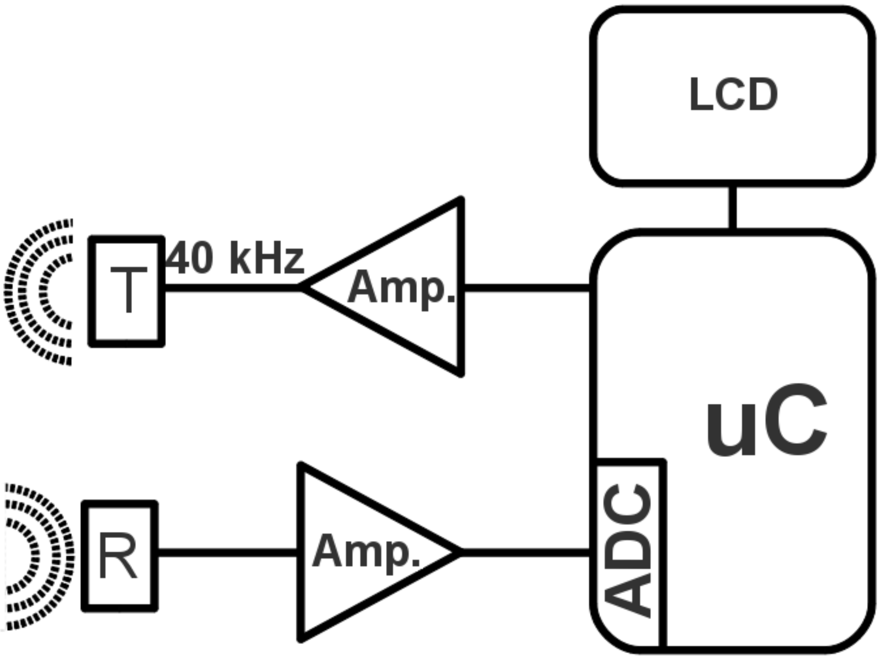

Figure 5.2. Ultrasonic transmitter test system scheme

An ultrasonic wave, its amplitude and intensity, are being suppressed while traveling through medium. This phenomenon is described by an analytic formula in (19). Additionally, some part of the wave is being wasted on a distortion while reflection.

$$I = I_0 e^{-\gamma \cdot x} \tag{19}$$

where:

I_0 – initial value of wave intensity for $x = 0$

γ – suppression coefficient

x – distance.

Figure 5.3 presents the extrapolated characteristic of the returning wave amplitude in relation to both the distance from the object and the object's area.

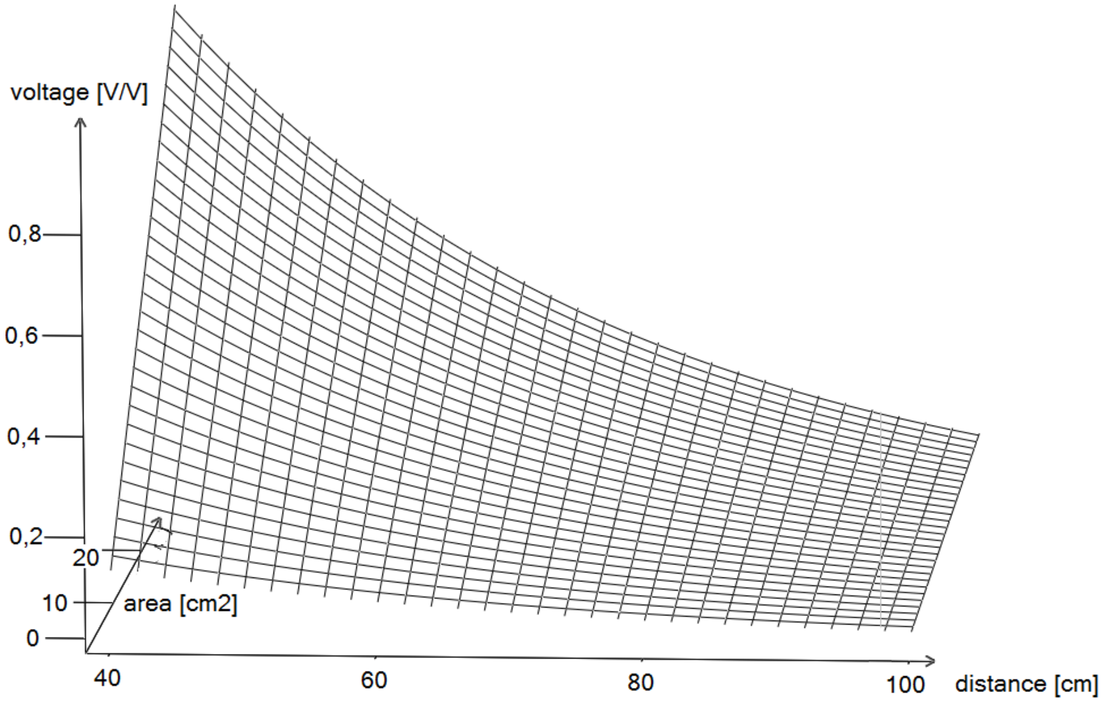

Figure 5.3. Extrapolated characteristic of the returning wave amplitude in relation to both the distance from the object and the object's area

Another important aspect is a detection sensitivity to the surface inclination to the wave propagation direction. The best possible scenario is when the inclination angle equals zero and the reflecting surface is smooth. Then the intensity of the returning wave makes it easier to detect it.

The relation between the obstacle inclination angle and the amplitude of the signal created by returning wave in transducer was tested using the 5 cm square-shaped metal plate. The characteristic with extrapolated results is presented in Figure 5.4. All amplitude data is normalized to the results from the largest plate and inclination angle equals zero.

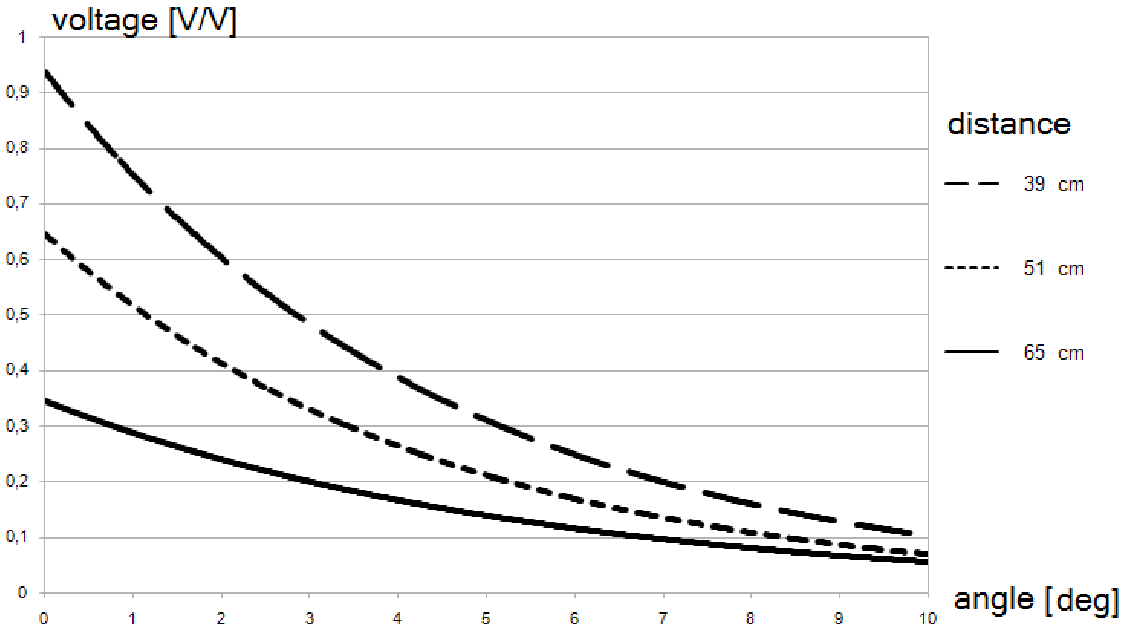

Figure 5.4. Characteristic of relation between the obstacle inclination angle and the amplitude of the signal created by returning wave in transducer

The presented results show what to expect from simple piezoelectric ultrasonic transducers when they are to be embedded into the distance finders and object detectors.

Designing a system that uses ultrasonic transducers for imaging or object detection and recognition, the structure and form of these objects ought to be taken into consideration. Since laws of physics make it difficult to reflect sound waves from some sorts of material, in some cases other method of object detection have to be used in order to provide high reliability. However, in some scenarios where optical based systems (cameras, etc.), for instance, glass door detection, ultrasound based systems are more handy and reliable.

Device design

Based on consultations with a group of blind people, some design assumptions were made. The device should be energy-friendly and also user-friendly. In other words, the device should operate a whole day on a battery without recharging and once turned on it should work without any configuration necessary. The design should be able to detect large obstacles in a range not less than 3-4 m. Also, the topic of an inertia was brought to attention. After the device has detected and informed the user about the obstacle, the user will have to have time to react accordingly, so the device delay is as short as possible. Thus, the device should be designed in a way that it can be treated as a real-time device. Assuming that the blind user will walk with maximum speed of 4 km/h (~1,1 m/s), by using the ultrasound sensors to detect the obstacle in a 4 m range (max), the times for a sound wave to reach the obstacle and return to the sensors would be: 0,024 s (for 4 m) and 0,012 s (for 2 m). The propagation time is very short comparing to the time which the blind user needs to walk to reach the distance of 1 m. So, the ultrasound technique is capable of fulfilling the real-time device assumption.

Ultrasonic range finders that provide a high reliability in detecting objects at the expense of a high accuracy (which is not so crucial for blind people navigation systems) usually compute distance with help of a time-of-flight. The velocity of an ultrasound wave depends on an elastic medium in which it is propagating and on this medium’s temperature. Having the information about the temperature helps to compensate for the distance measurement error.

Most of the available ultrasound range finders differentiate between ultrasonic receivers and transmitters [Kum11]. In other words, one channel for the distance measurement requires both a transmitter and a receiver to be a separate transducer. This forces the application of twice the number of transducers than there are ultrasound distance measurement directions. This chapter presents the multichannel ultrasonic distance range finder which employs only one transducer for each channel. This helps to reduce the device size which is crucial in mobile systems. Both of these solutions are presented in Figure 5.5.

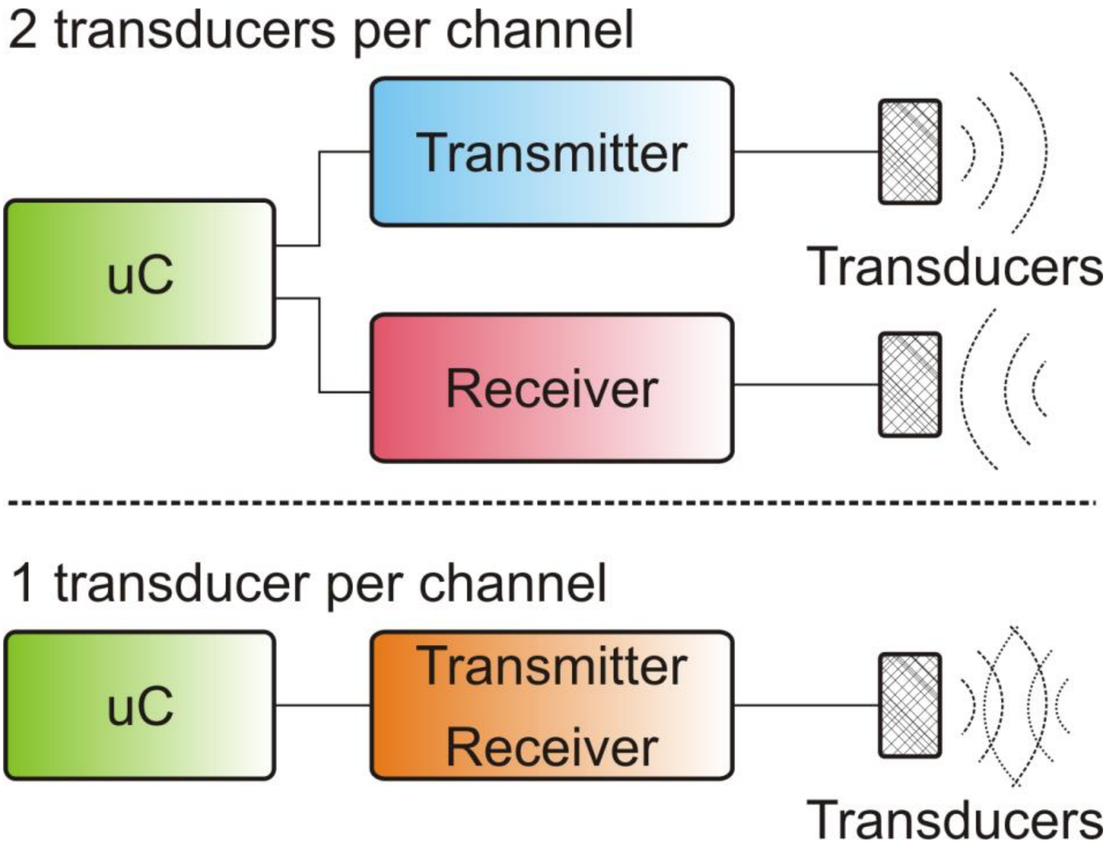

Figure 5.5. Two transducers per channel solution (top) and one transducer per channel solution (bottom)

The perfect ultrasound solution for the blind people navigation system would be the one if ultrasound waves were sent in every direction to create a full *3D* distance model. However, it is very hard to implement such volume of ultrasonic transducers in regards to the mobility, size and batteries limited energy capacity of the devices for blind people. In this chapter a six channel driver is presented. A complete substitution of a white stick could lead to situations in which blind people – used to white sticks – feel insecure. That is why the six transducers check for obstacles in front of and on both sides of a blind person, who still can sense obstacles with a white stick which occur from the waist to the ground level. This transducers layout is presented in Figure 5.6. This layout makes it possible to detect dangerous obstacles with a high reliability and in addition to that the low volume of ultrasound transducers allows the device to be small, mobile and comfortable to be carried with. A simple block diagram of the multichannel ultrasonic range finder is presented in Figure 5.7. Ultrasonic transducers are piezoelectric elements.

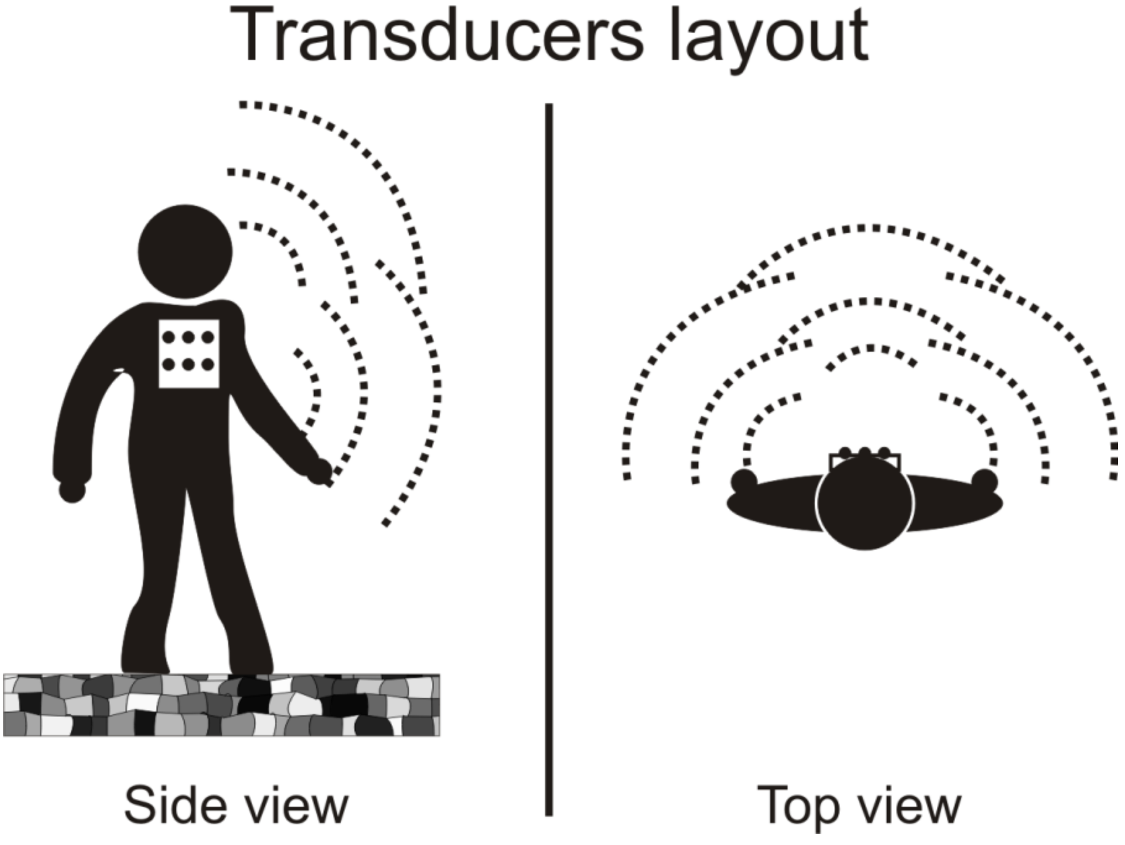

Figure 5.6. Transducers layout and ultrasound waves directions in the *MOBIAN* device

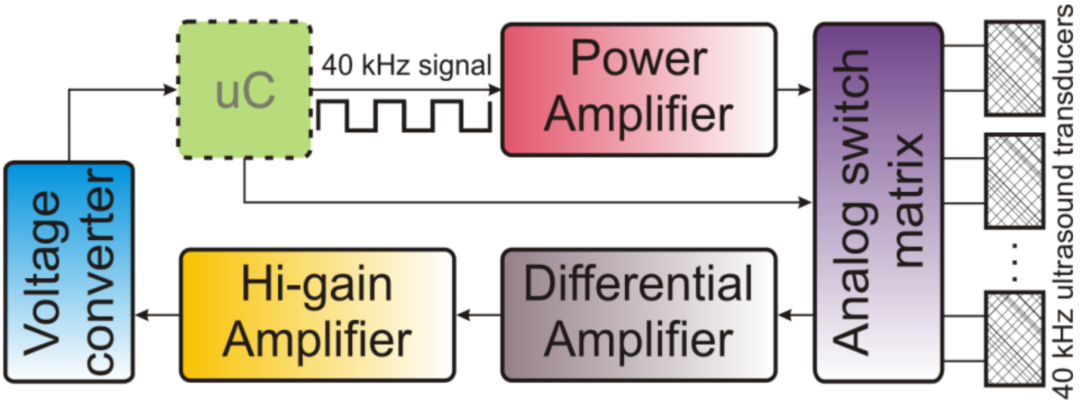

Figure 5.7. Block diagram of the multichannel ultrasonic range finder front-end (a microcontroller is not implemented)

They are often excited by a 40 kHz square wave (*http://download.maritex.com.pl/pdfs/se/40str-16.pdf*). The measureable distance depends on the amplitude of this wave. Therefore, the microcontroller generates the 40 kHz square wave which is amplified to obtain a greater distance. In this way the designed driver can be used by many different microcontroller families. The transmitter and receiver circuits are isolated by analog switches. This allows it to use only one transducer in each channel. The other advantage of this solution is that receivers circuits are protected from the high-voltage square waves. If the wave from the transmitter encounters some object, it is reflected. The voltage amplitude of the returning wave after transformation in one of the transducers is low. The signal from the wave is distorted due to the wave interference which occurs during the reflection. To detect the returning wave a two stage amplifier was applied. For the first stage a differential amplifier was used. This helps overcome the distortion problem. Since the ultrasonic driver is to be controlled by the wide range of silicon devices, an output voltage conversion block was applied.

The input and output interface of the ultrasonic range finder was designed to be used by almost every microcontroller available despite its peripherals and computational power. A switching flexibility allows signals to be multiplexed among receivers. One is able to transmit signal from a particular transducer and to receive the reflected wave on the other transducers. This is helpful for detecting objects which surfaces are inclined to the direction of the wave.

Various algorithms for the obstacle detection can be easily implemented, for instance, detecting a single obstacle, multiple obstacles situated in one line, an inclined surface detection, etc. [Per09]. If only a microcontroller has enough free pins, a second ultrasonic driver can be implemented, providing some extra channels for measurements.

System examination

Every piezoelectric transducer is excited by a signal from a microcontroller. This signal gets amplified to achieve a greater maximum distance. Once the control signal becomes constant, the transmitter should be disabled and the receiver should be enabled to monitor if the sent wave has returned. The tests have shown that piezoelectric transducers have some inertia. It means that as soon as the excitation signal stops, the transducers need some time to stop generating wave and that their pin-voltage goes down to zero. Therefore, to protect the receiver circuits from the high voltage of the weakening transducer signal and of course to avoid false measurements (a high level signal could be interpreted as a wave reflected from some obstacle which is situated in a very close proximity to the transducer), the signal from the transducer should be directed to the receiver only after the pin-voltage stabilizes. This delay determines the minimum distance that could be measured. The tests have shown that by applying a resistor as close as possible between the transducer pins, the delay can be shortened. The difference between the delay in transducer with and without the resistor is shown in Figure 5.8. However, the delay Δt is less than 1 ms, which does not affect the device real-time assumption.

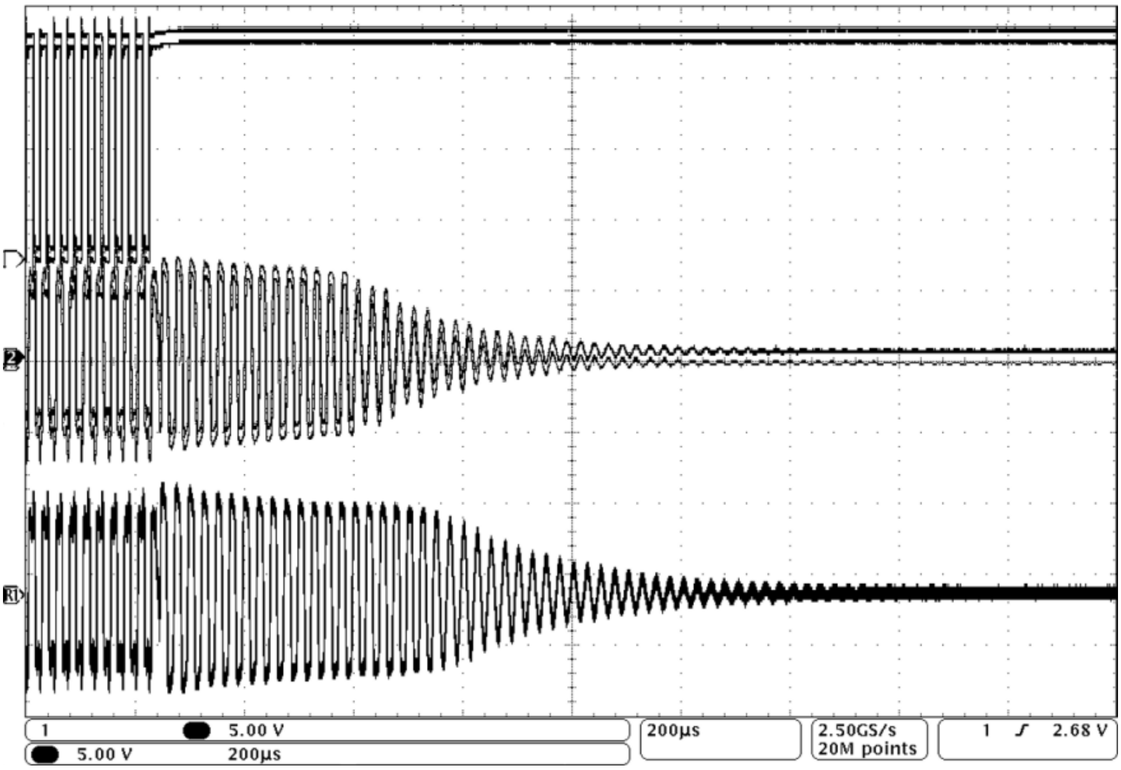

Figure 5.8. Difference between transducers self-suppression times after the excitation signal stops generating square wave – the excitation signal (top), the signal from transducer without the extra load resistor (middle), the signal from transducer with the extra load resistor (bottom)

Tests have shown that the designed receiver circuit works properly. A flat surface obstacle was placed in approximately an 80 cm distance from the transducer. The returning wave is presented in Figure 5.9. After the amplification the signal shape is presented in Figure 5.10. Distance measurements based on a time-of-flight parameter usually disregard a shape of the signal and detect only an amplitude above a certain value. That is why the amplifier is allowed to clip the output signal in order to increase the maximum distance. The applied output voltage conversion block adjusts the signal for the 0-3 V tolerance level microcontroller input pin. The final signal shape of the ultrasonic range finder output pin is presented in Figure 5.11.

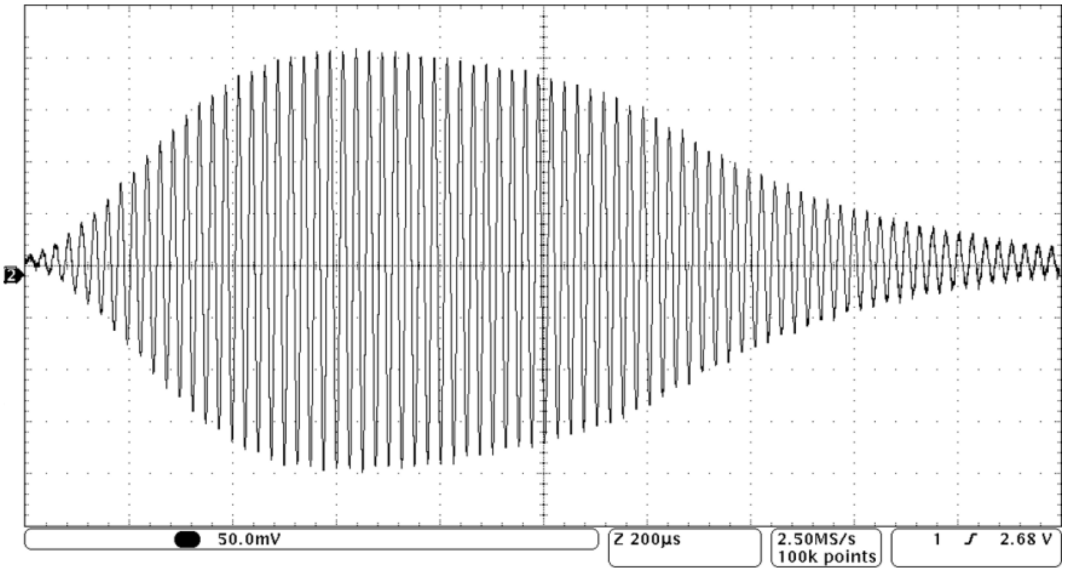

Figure 5.9. Returning ultrasonic wave signal on transducer pin

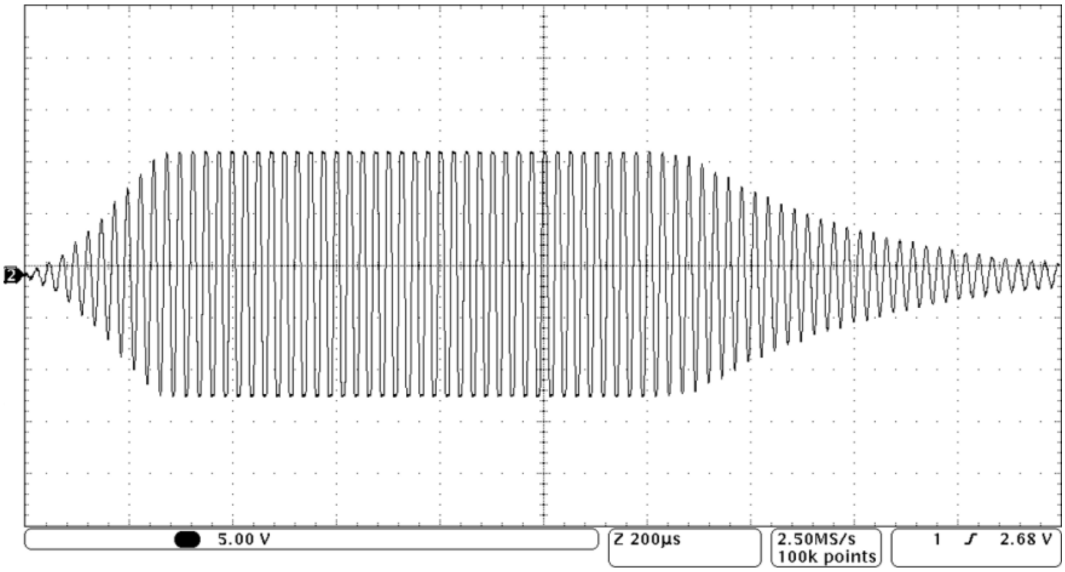

Figure 5.10. Returning ultrasonic wave signal after the amplification

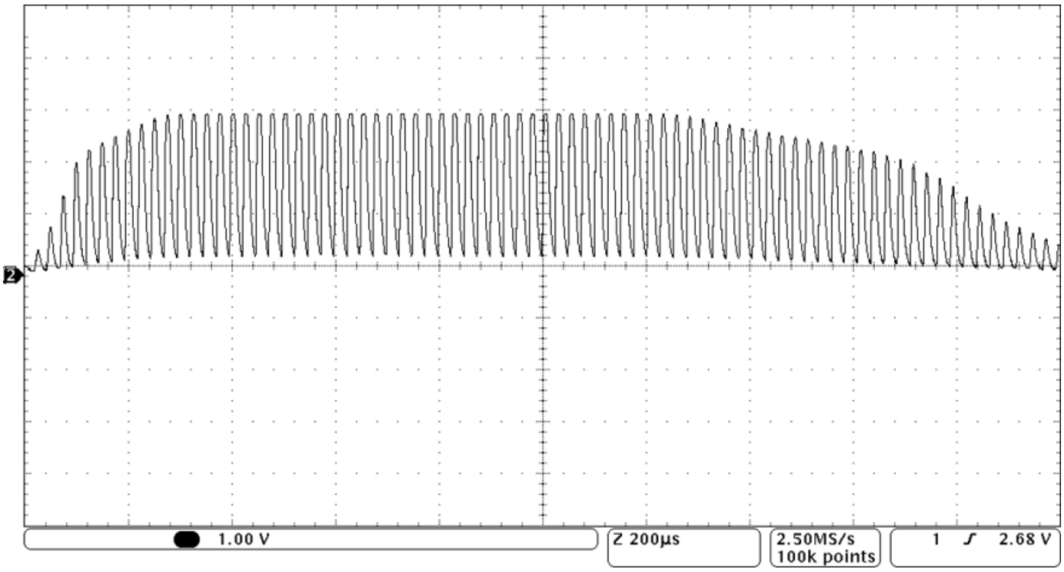

Figure 5.11. Returning ultrasonic wave signal after the amplification and the voltage conversion

In navigation systems for blind people, ultrasonic range finders generally notify about the nearest obstacle detected. This is sufficient enough because the blind person should be given a minimum but sufficient piece of information which assures safety and is not confusing. Nevertheless, the designed multichannel ultrasonic range finder can be used in other devices and not only in the blind people navigation systems. That is why the ultrasonic driver is able to detect more than one object on the way. A small object was added between the transducer and the flat surface obstacle to the previous test scenario . The returning wave is presented in Figure 5.12 and the final signal shape on the ultrasonic range finder output pin is presented in Figure 5.13. With help of some algorithms, the microcontroller is able to detect two obstacles on the way and to calculate their both distances from the transducer.

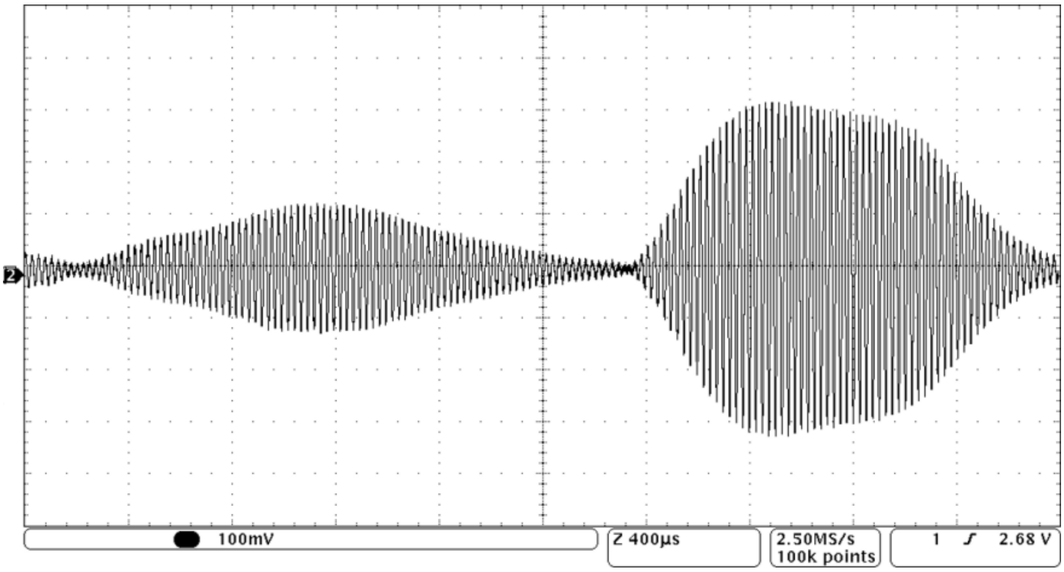

Figure 5.12. Returning ultrasonic wave signal on transducer pin – reflected from two obstacles in one line

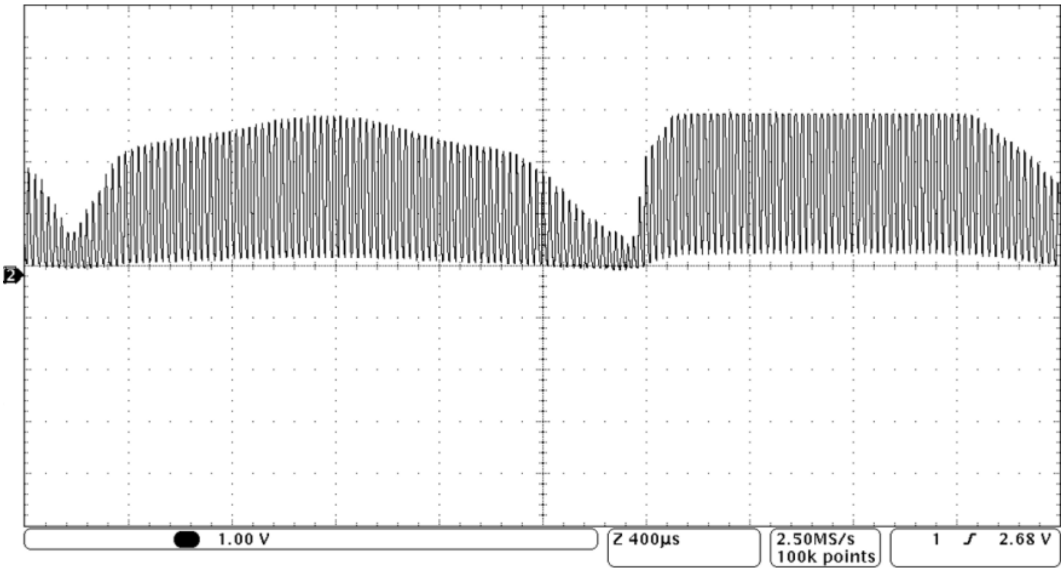

Figure 5.13. Returning ultrasonic wave signal reflected from two obstacles in one line – the signal after the amplification and the voltage conversion

The ultrasonic driver was designed to detect obstacles in the range that lets blind people to be informed about the likely danger and gives them enough time to react properly. The maximum distance detection depends on how big the object surface is. For obstacles large enough to cause harm to a person, for instance, chairs, lamps, shelves, etc., this maximum distance is over 4 *m*. The maximum distance was tested in a room. Between the transducer and the wall, two flat surface objects were placed. The final signal shape on the ultrasonic range finder output pin is presented in Figure 5.14.

The common problem with ultrasonic range finders is the detection of tilted surfaces which is due to the sound waves propagation physics. Figure 5.15 shows shapes of returning waves reflected from a flat surface obstacle tilted by 0, 10 and 45 degrees. One can see the significant amplitude reduction. However, the last tilted surface could still be detected. The final signal shape on the ultrasonic range finder output pin presented in Figure 5.16 shows the amplitude of the returning wave reflected from the 45 degrees tilted surface. This amplitude is over 0,7 V.

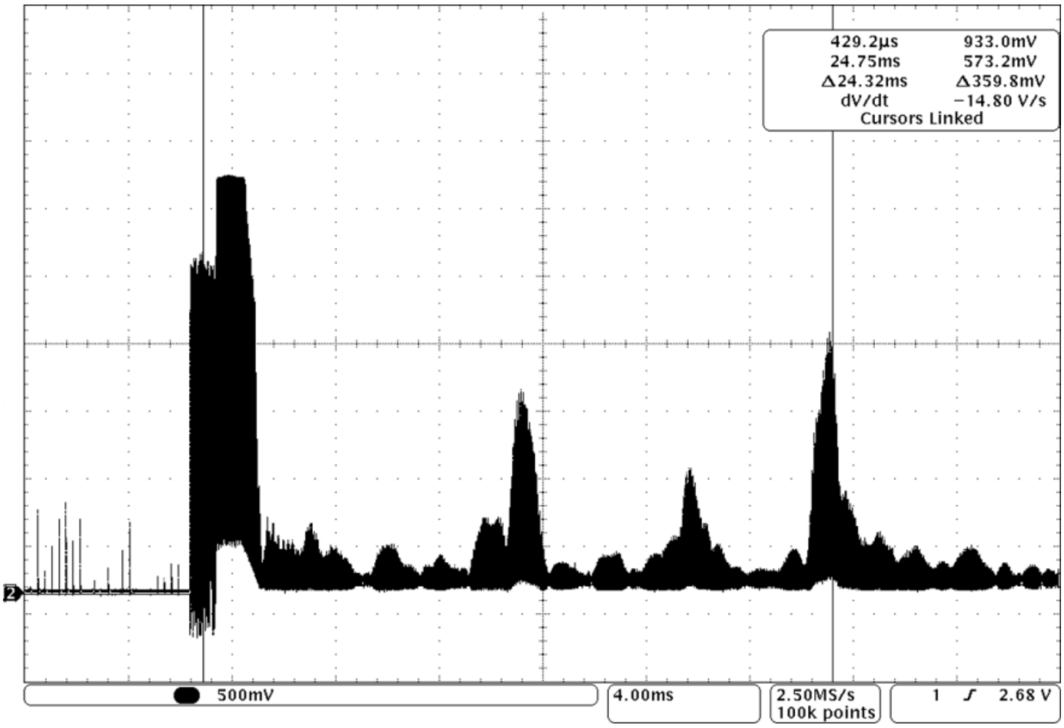

Figure 5.14. The final signal shape on the ultrasonic range finder output pin in maximum rage test

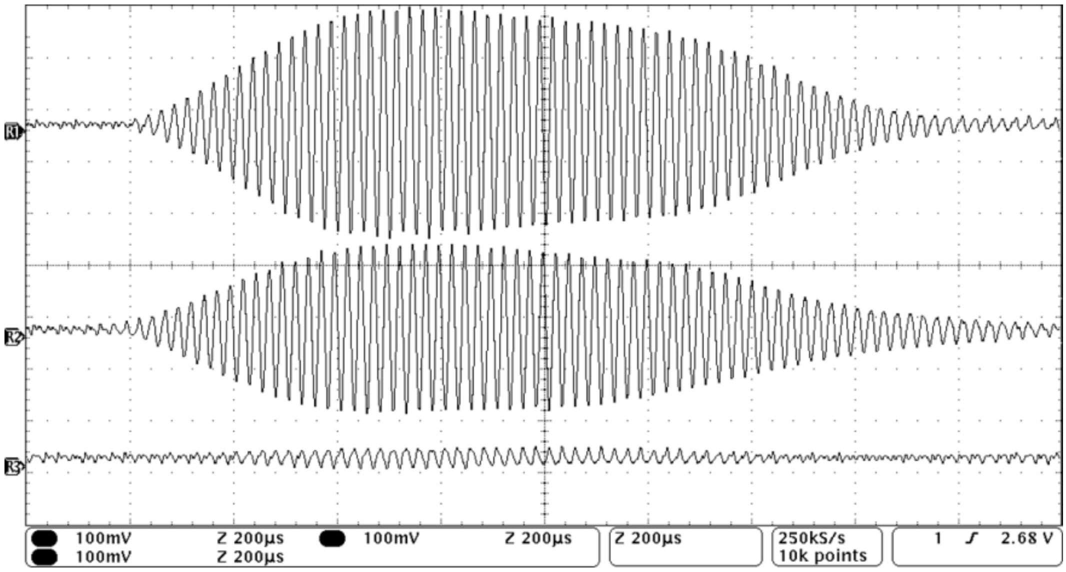

Figure 5.15. Differences between the returning ultrasonic wave signal reflected from obstacles tilted by 0 (top), 10 (middle) and 45 (bottom) degrees

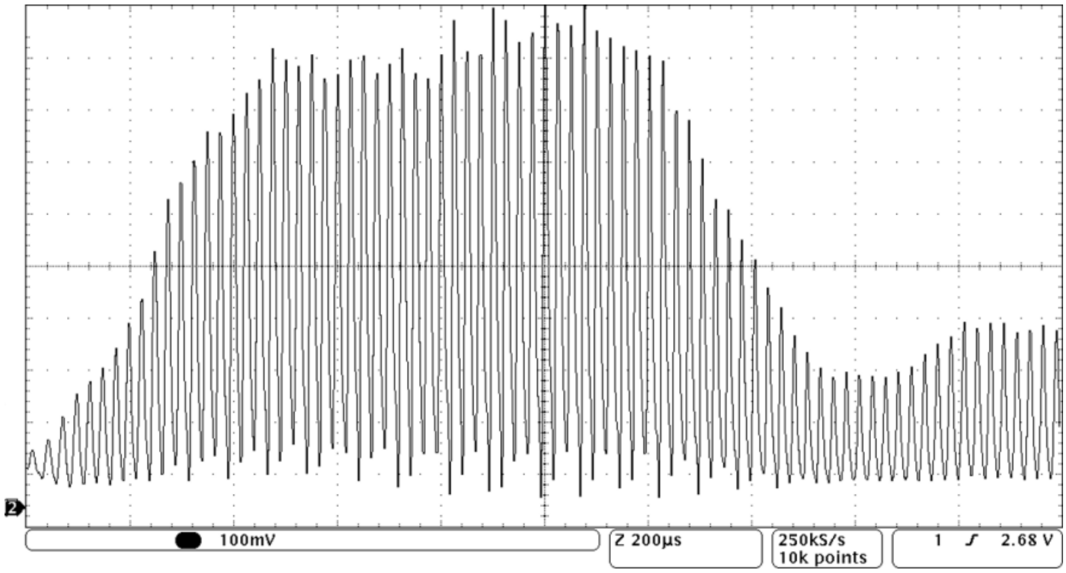

Figure 5.16. Returning ultrasonic wave signal reflected from the obstacle tilted by 45 degrees – signal on output pin

CHAPTER 6: VIBRATING BRACELET INTERFACE

It can be said with no doubt that electronic devices have blended into people's lives for good. They are present in almost every branch of industry worldwide. The constant technological progress makes everyday life easier for people and also comes in handy for impaired people. Scientists and engineers develop electronic aids for handicapped people. All over the world there are many visually impaired people, especially in the developing countries. A common problem for them is their safety outside their houses, particularly in the unknown areas. Therefore, nowadays many navigation assistant devices are being worked on and some of them are already available on the market [Dak10]. Some of those aids use acoustic signals or speech synthesizers and a headset to communicate with a blind user. Consultations with visually impaired people have shown that, although this approach is suitable for familiar and indoor environments, it is not the best solution for outdoors and unpredictable areas to jam raw, acoustic information from surroundings.

Some aids for blind people employ tactile interface for communication. Usually, stimulant points are on fingertips, palms or bellies [Cos14], [Dak10], [Vil12]. Nevertheless, most of these interfaces either occupy a palm or carry too little data, for instance, distance and direction from obstacle.

Electronic devices development for blind people should strongly consider employing only low-power electronic components and techniques to assure the minimum of a whole-day operation without changing or recharging batteries. Nowadays, components manufacturers offer special low-power products lines, therefore creating low-energy devices from hardware which is available on the market is less complicated. Usually, the difficulty is to create some embedded software that drives the whole system in a way that all the low-power functionality is utilized in the optimized way to prolong the battery life. To do that some software creation techniques can be applied. One of these techniques is called energy debugging [Gel12].

By writing the firmware for some device and at the same time controlling the power consumption of that device and if possible change the code to get rid of unnecessary current peaks drawn from the battery, the developer is able to minimize the power consumption. Sometimes, this technique comes in handy while trying to detect why the device resets itself due to the short-term output current demand which can be far greater than the voltage regulator or the *DC/DC* converter can provide.

There are some solutions already available on the marker for energy debugging. One of them is Advanced Energy Monitoring (*AEM*) tool from Energy Micro. Every development and starter kit from Energy Micro has the *AEM* tool implemented on-board and the supporting software is provided for free.

The vibrating bracelet interface is based on a microcontroller which can cooperate in the energy debugging cycle (Figure 6.1).

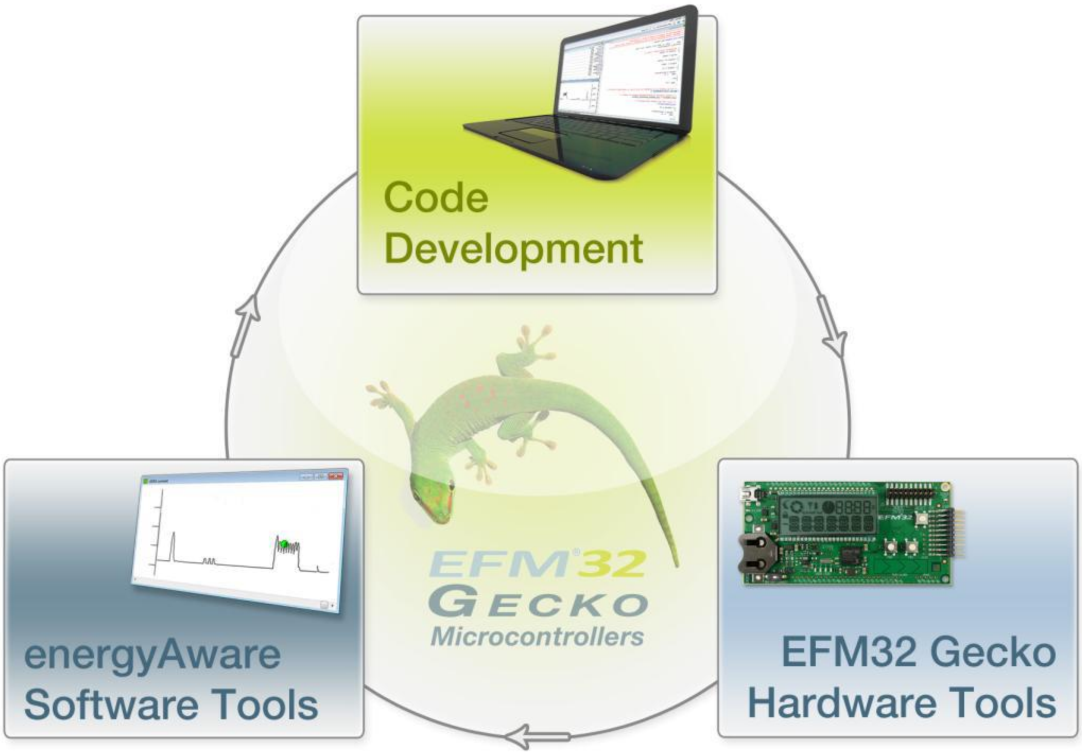

Figure 6.1. Energy debugging cycle for minimizing the power consumption of the vibrating bracelet

Bracelet interface overview

There are many interfaces for communication between human and a machine. When it comes to the implementation of one in some device for blind people, a collection of usable interfaces is narrowed down. Nevertheless, there are still some tactile, vibrating and sound interfaces that the developer can employ. All around the world there are groups of scientists that are working on various kinds of brain-computer interfaces. Although these interfaces sound promising and when perfected could revolutionize the way people communicate with machines, it would be hard to implement them into blind people devices. Usually, the brain-computer interfaces make it possible to communicate in a human-to-computer direction and not the other way. The feedback is often created via some kind of display/visual interface, which is useless for blind people. Granted, there are also experiments being conducted to transfer data to a human brain, but the works is proceeding very slow due to the fact that the human brain is highly complex and it is still uncharted for scientists. Therefore, even real-time prototype applications are not on the horizon. That is why interfaces for blind people have to be designed based on traditional and more natural and known for them techniques.

The electronic aids for blind people should interfere with users' movements and perception possibilities as little as they can. Therefore, a multipoint vibrating bracelet interface for various applications is being presented. The bracelet is carried on a wrist, thus is does not restrain movements or occupy a palm. A bracelet block diagram is presented in Figure 6.2.

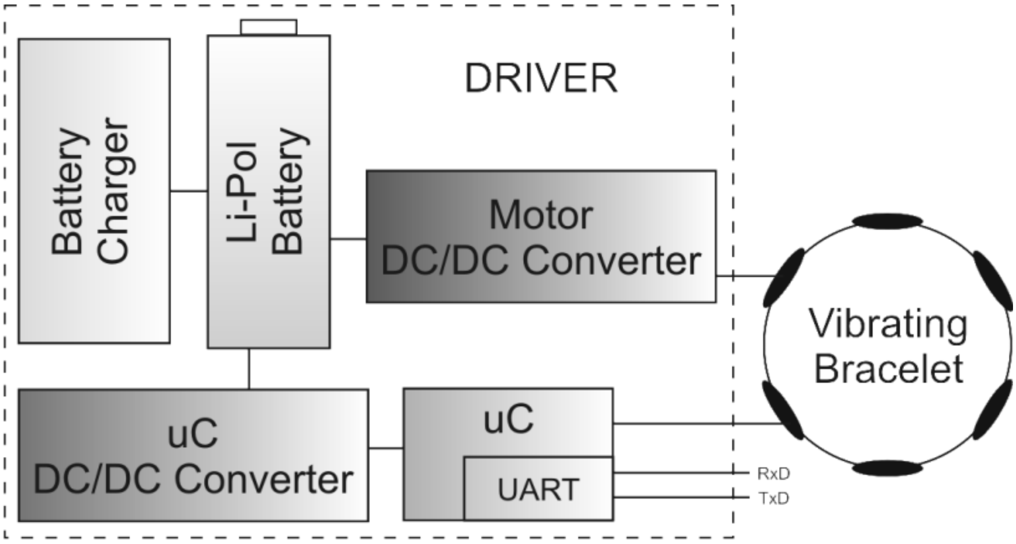

Figure 6.2. Multipoint vibrating bracelet block diagram

Most people, not only the blind ones, are used to having a watch of some kind on their wrists, so this is a natural place for the bracelet. Some experiments were conducted to assure that the wrist is a good place to feel vibration stimulants [Bog11].

The bracelet prototype includes six vibrating motors, evenly distributed on a wrist. The motors are connected to a driver. The prototype device used in the tests is presented in Figure 6.3.

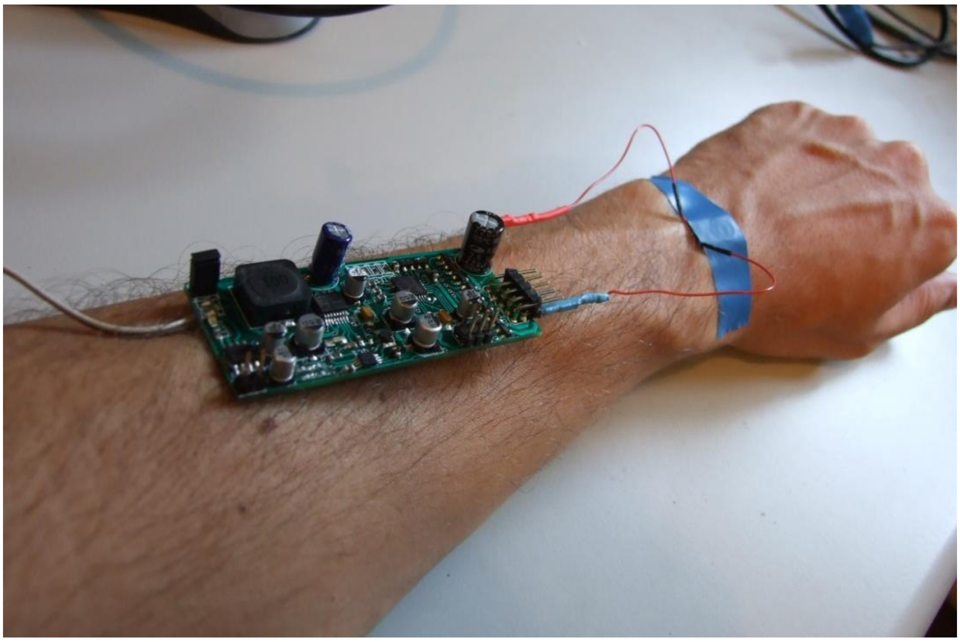

Figure 6.3. Vibrating bracelet prototype

Since the whole device should be light weighted, its power supply is a *Li-Pol* mobile phone battery. To assure a low-glitch level in the driver, the separate *DC/DC* converters for a microcontroller and for motor transistors were used. A 5 V battery charger chip was also implemented. By programming an onboard low-power microcontroller, a different signaling algorithm can be accomplished. The communication with the vibrating bracelet is done via *UART* interface.

Vibrating signal schemes

In order to pass a lot of information to a blind user, some schemes have to be implemented to drive vibration motors on the bracelet. To inform a visually impaired person about a detected obstacle and its distance, an impulse modulation is used. In a certain period of time a single motor is being turned on and off again. This switching frequency is related to the distance and for the user it feels like a vibration strength. Since there are six motors, a multipoint vibration is suitable either to inform about an obstacle direction (therefore, a bracelet can inform about multiple objects at the same time) or the height on which the obstacle occurs. Another way to inform about obstacles is to send single, detectable, strong, short vibrating impulses of various frequencies. By changing this frequency a user can also be informed about the distance. Variation of this signaling scheme can be used to warn a blind person about specific, yet frequently recurrent scenario objects, like for instance, stairs going up and down or curbs. This variation utilizes a constant period of time, for example 1 or 2 seconds, and in this time a countable, short impulses are being sent. Their number determines a pre-learned object name (stairs, curbs, etc.). In early stages of teaching a blind person how to use the vibrating bracelet, the mentioned pre-learned object vibration can be implemented in all six motors simultaneously in order not to confuse the users and help them to be able to differentiate between pre-learned object vibration and the distance from obstacle vibration.

Some vibrating schemes are presented in Figure 6.4 and Figure 6.5.

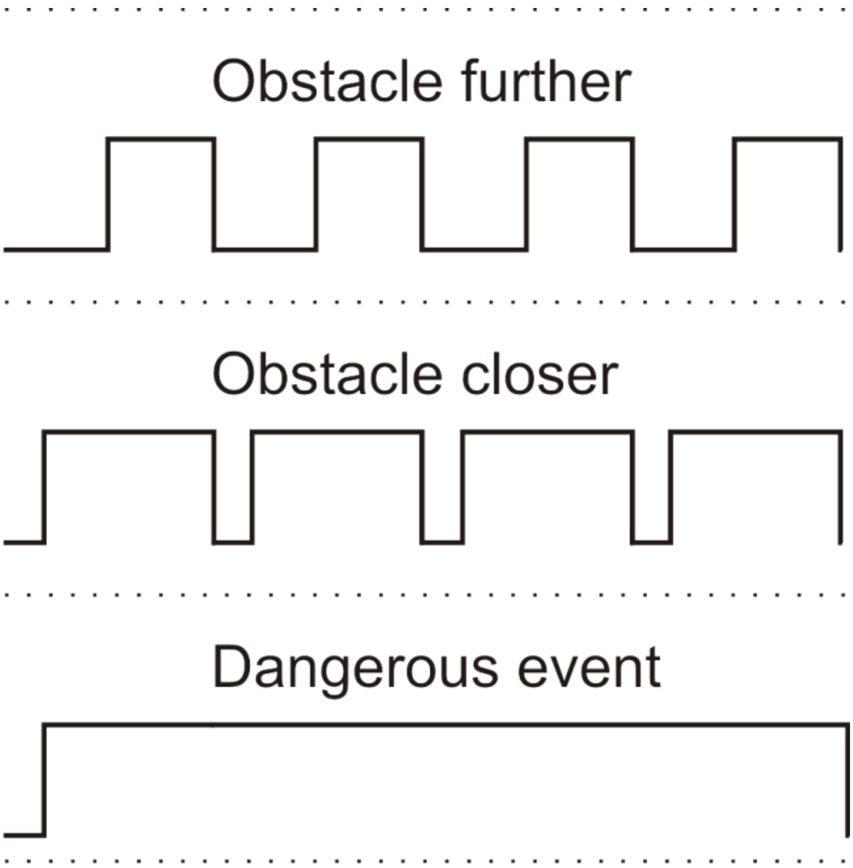

Figure 6.4. Vibration schemes for coding detected obstacle distance

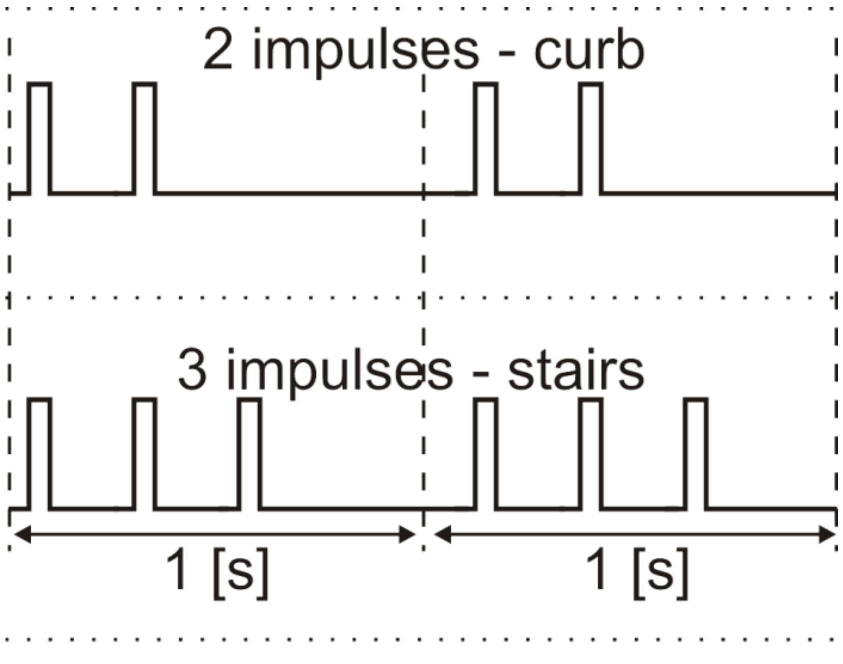

Figure 6.5. Vibration schemes for pre-learned objects: curb and stairs

Apart from informing the visually impaired people about obstacles, distances and pre-learned scenario objects, the bracelet is also capable of sending commands and indicators to the users by means of a multipoint vibration. By creating a vibrating pattern, its direction, duration and location, the bracelet can send commands to turn left, right, to inform about transferring navigation data, calculating route and even to inform about an incoming call, a received *SMS* or an e-mail when connected to an external device. Thanks to the commonly used *UART* interface for the communication with the driver, the bracelet can be used not only with navigation assistant devices, but also with mobile phones (via a *BlueTooth SPP* protocol) or computers (via an *UART/USB* converter).

Some vibrating commands schemes are presented in Figure 6.6.

Bracelet tests and results

Tests have shown that the six vibrating points available in the bracelet seem to be optimal to determine vibration location and to recognize vibration patterns. However, in case of people with thick wrists or people who have tested the bracelet for a while, additional vibrating points can be added to enhance the vibrating patterns set – one driver is capable of controlling up to 10 motors.

Every new user needs time to learn indication patterns and what each vibration motor function means. The recommended experience level is that the user is able to recognize all indications in real-time without breaking one’s concentration.

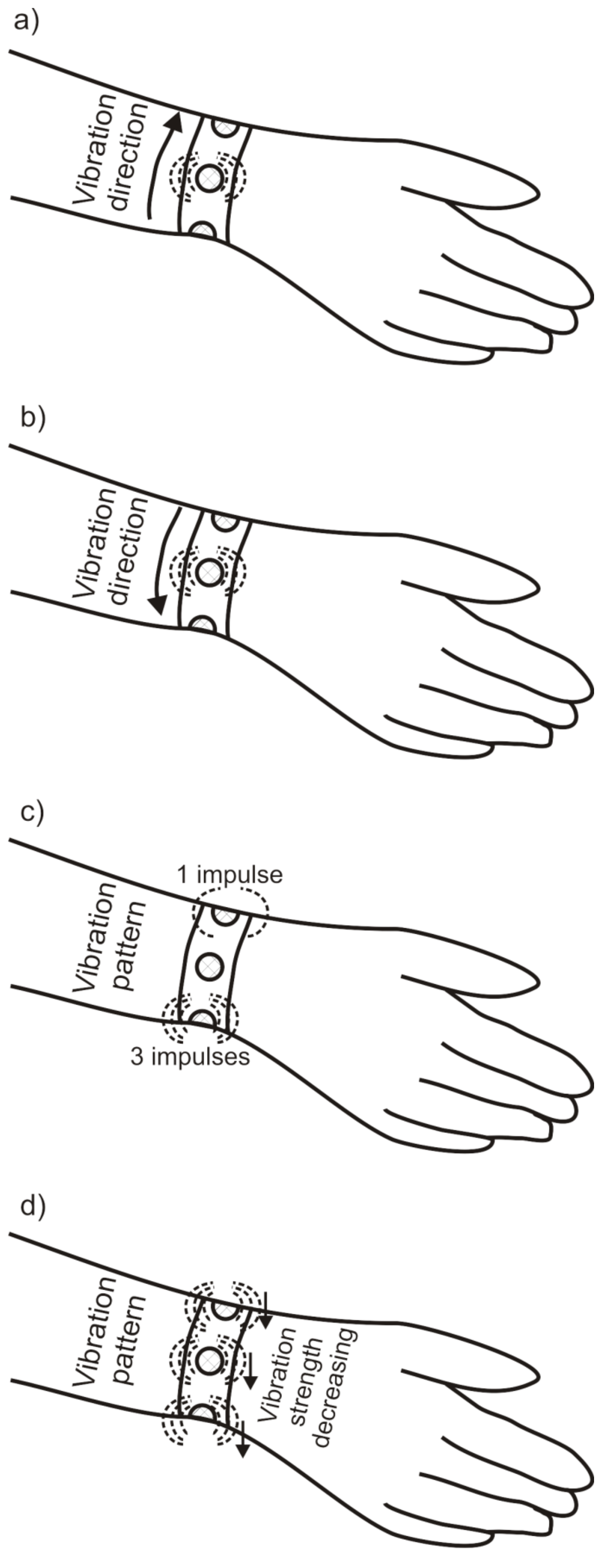

Figure 6.6. Vibration pattern schemes for pre-learned commands:
a) Counter clockwise signal direction
b) Clockwise signal direction
c) Different impulses values on different motors
d) Vibrating signal strength decreasing on all motors

Tests have shown that both vibration strength, minimum impulse time and time between them can be slightly different for each person to be able to differentiate all vibration schemes. Therefore, vibration signal strength, patterns, distance alerts can all be customized to assure a higher user-friendly level and also to reduce learning time. Scheme learning takes some days and it is more efficient when a user learns first by themselves to locate a single vibration or multi source ones and then simple and more advanced vibration patterns. In the end, when one is used to the mentioned schemes, one should learn how to quickly differentiate them and count short impulses. Once a user feels comfortable with bracelet signals and quickly realizes the differences between all schemes, it is time to start real-time tests in the real environment.

After a learning period, the users are able to respond fast to alerts about obstacles and their directions. Indications about detected specific objects like stairs or curbs are also recognized, as well as other scheme commands.

CHAPTER 7: REMAINING *MOBIAN* SUBSYSTEMS

Apart from the parts of the *MOBIAN* system described above, there are other subsystems available that were developed to be included into the *MOBIAN*. All of them were created as a result of the consultations with the blind people to help them overcome their everyday issues. One of the subsystems is a navigation assistant based on *GPS* and *GSM* technology. The other is a scanning device.

GPS and *GSM* based points of interest localization system for blind people

The *GPS/GSM* based localization system is designed to help blind people navigate and find points of interest (*POI*) important for them in urban areas. When the *GPS* localization is not available for some time or the system has just been turned on in an unfamiliar place for the blind user, where one cannot get a *GPS* fix, the *GSM* based localization is being used in order to find a specific *POI* or to alert a family member or emergency services about the blind user's approximate location.

RELATED WORK

Navigation devices and systems of different kinds have been used since ages. Technology advance makes it possible to develop low-priced, yet accurate devices for localization purposes. Since most of these devices use some kind of a display to present information, they are not suited for the visually impaired users. However, there are some systems being developed specifically and only for blind people [Dak10]. Unfortunately, those kinds of systems usually have limited functionality, like for instance, informing users about a specific *POI*, pedestrian crossings [Udd05]. Nonetheless, using a *GPS* based application is only proper when the receiver has a clear sky view. Inside of buildings and/or underground areas, the *GPS* signal is not received, thus getting a position fix is problematic. There are some solutions, including other sensors, to localize and navigate when a *GPS* fix was accessible and due to entrance to a building, is no longer available [Kim08], but in situations where a blind user turns on the device for the first time in places where the *GPS* signal is too weak to get a fix it is hard to get a reference to a global position. That is why the *GPS* based system with *GSM* localization capability has been carried out.

Electronic navigation assistants for blind people are difficult to develop. *GPS* based devices, even with some position correction functionality [Sun12], do not provide high enough reliability to safely navigate a blind person through an urban area. Even a 5 m position error while locating a pedestrian crossing can be dangerous for visually impaired users. That is why information about specific, important for blind people *POI*, should be considered rather as some advice than a navigation guide like in car navigation assistants. When the *GPS* signal is too weak to get a localization fix, a *GSM* based localization comes in handy. There are many techniques to get a pinpoint location by using *GSM* network [Ibr12]. *RSSI* based systems are accurate, but they need a fingerprint map or an architecture map to correlate *RSSIs* from *GSM* base stations with pinpoint location and these are not always available for some areas [Ahr10]. There are some systems which provide high reliability and were created especially for blind people. However, these systems often employ components, which have to be embedded into existing infrastructure, for instance *RFIDs* [Che10a], [Chu08], thus these systems are expensive if one wants to have them installed on large areas.

Another technique uses the fact that every *GSM* base station can be identified by special codes. Those codes make every single *GSM* base station unique in the world. When cellular modem is enabled it can check which base stations are available in the nearest location. The base stations are not only the ones that the cellular modem can be connected to, but these are all the base stations which are advertising their availability. Among other information, every base station transmits the base station specific numbers:

- Mobile Network Code (*MNC*) – every country has its unique code (the code for Poland is 260),
- Mobile Country Code (*MCC*) – every cellular network in each country has its country specific code (some of the polish cellular networks codes: Plus (01), T-Mobile (02), Orange (03), Play (06, 98), Netia (07)),
- Location Area Code (*LAC*) – every partial area of each cellular network has a network specific code (2 bytes),
- Cell ID (*CID*) – every base station has a specific *ID* unique in a local area of every cellular network (at least 2 bytes).

There are databases, in which those identifiers can be correlated with base station longitude, latitude and approximate signal range [Lan09].

SYSTEM OVERVIEW

The system block diagram is presented in Figure 7.1. The system runs *ARM* Cortex-M3 based low-energy *EFM32* microcontroller and embeds a *GPS* module for a pinpoint location. Navigation assistants usually use *POI* database to provide information about some specific locations, e.g. a gas station, restaurants, traffic accidents, etc. *POI* which blind users could benefit from should be far more extended than a widely available *POI* used in common databases, like Google Places. Apart from the standard places, that database should include information regarding pedestrian crossings adapted for blind people, hospitals, special centers for visually impaired, bus stops and many others. Also, there should be a possibility to easily include specific, customized records, like places from blind user environment, e.g. university campus buildings. A small prototype database was embedded into microcontroller memory. With a clear sky view, the *GPS* localization accuracy is sufficient for guiding a blind user. When entering a building, where *GPS* localization is no longer available, a *GSM* Cell ID based localization is used. Thus, a *GSM/GPRS* module is embedded.

Cell ID based localization technique does not provide great localization accuracy, nevertheless blind people navigation inside buildings is difficult, even with the 1 m accuracy, without external sensors, cameras, building architecture, etc., due to users' visual impairment. Therefore, the Cell ID localization is used just to inform the blind user about specific *POI* in the nearest area in the selected range and to send possible location via a distress *SMS* in case of some emergency or an accident. Small head phones are used for feeding users voice commands and information about *POI*.

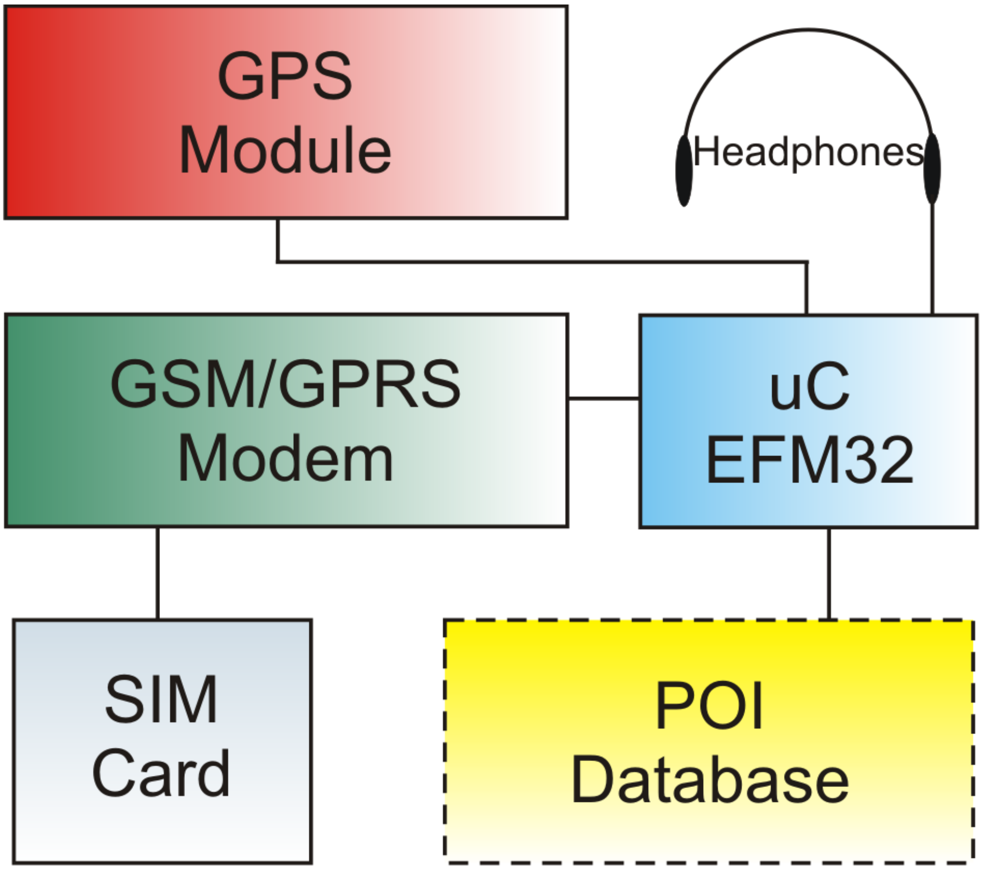

Figure 7.1. *GPS* and *GSM* based points of interest localization system for blind people – block diagram

ACQUIRING *GSM* STATIONS LOCALIZATION

Practically, every *GSM* modem has the ability to check base stations codes, desired for *GSM* localization (*MNC*, *MCC*, *LAC*, *CID*). The system for blind people checks the codes not only from a base station, which it is currently connected to, but also base stations in the area (with signal range). This is achieved due to the fact that checking only the main base station (mainly the one with the strongest *RSSI*) would give accuracy of hundreds of meters or even a couple of kilometers. By checking all the available base stations codes, the system is able to increase the localization accuracy.

There are many ways to link base stations codes with their global position and range. The easiest one is to create a database of base stations with their codes and global localization and compare the data from a *GSM* modem against it. It would operate without any Internet connection, however would consume large quantities of memory. Since the system has a *GSM/GPRS* modem onboard, it can check external services. One of those services is run by Google, so cell phones even without any *GPS* module can obtain their approximate positions and users can run Google Maps as well as other applications. Google has not provided *GSM* based localization by itself as an official *API* yet, but still it can be accessible [Lan09]. Other service which helps to locate a *GSM* base station is the OpenCellID project. It is an open source and has documented *API* for queries.

PRELIMINARY TESTS AND RESULTS

The system prototype was designed and is presented in Figure 7.2. In a building, where the *GPS* fix could not have been established, the *GSM* localization service was enabled. Afterwards, base station codes were correlated with base stations positions and ranges via Google service. Sample results are presented in Figure 7.3. Every visible base station is presented with a blue circle. Circle center is a base station location and circle radius is a range. The black dot is an actual device location in the building. The red shape is the area where all the signal areas from base stations overlay. That is the likely *GSM* localization based fix. The last step for the device is to check if there are any important *POI* for blind users.

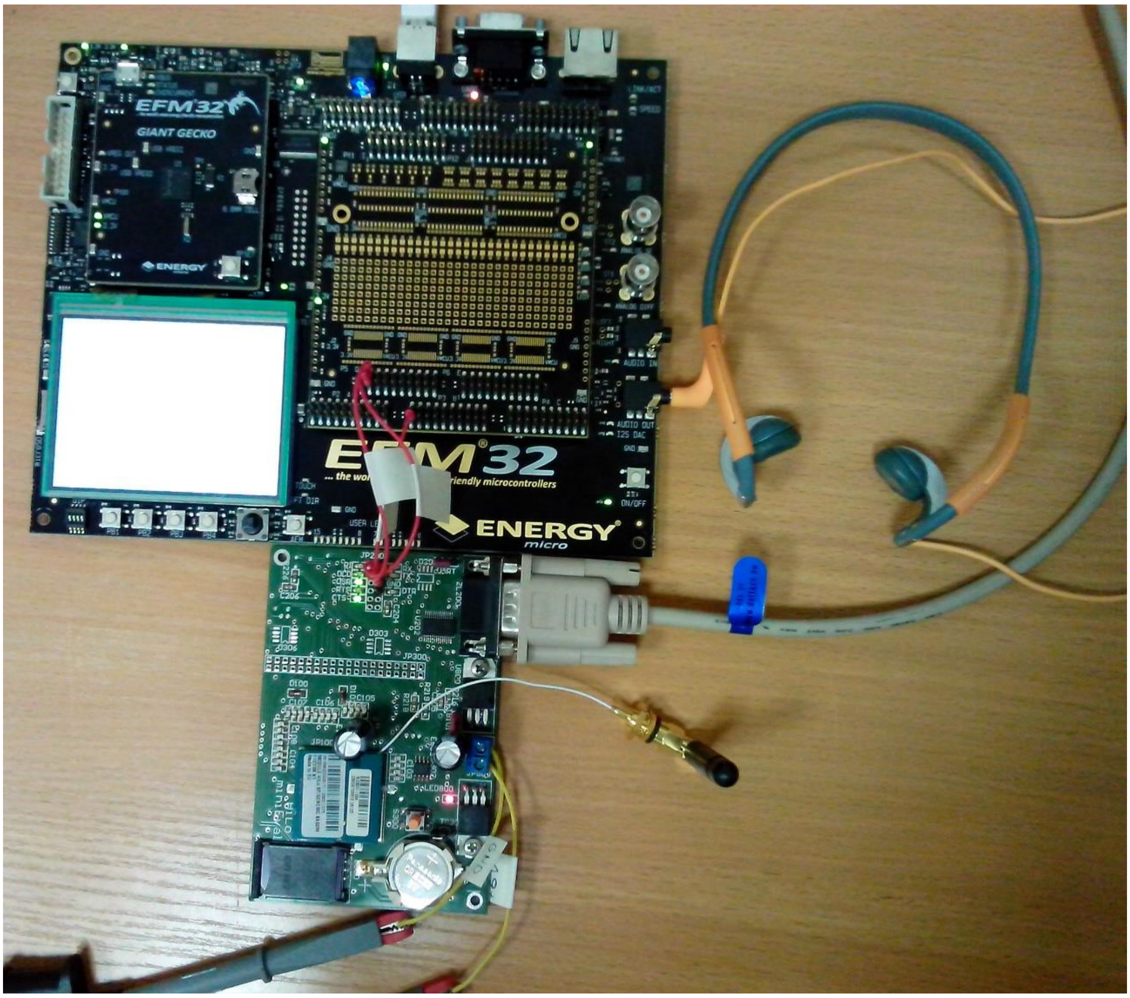

Figure 7.2. *GPS/GSM* device prototype

The working prototype of the described system provides platform for future tests with blind people. The *GPS* position fix is accurate enough to inform visually impaired people about nearest *POI*. In cases when the *GPS* signal is too weak, the *GSM* based localization is used, providing information about *POI*. This information is useful for blind people, who are lost in unfamiliar areas and they cannot get assistance from any people nearby. The option of sending users' position via *SMS* is also very helpful. In future, other localization algorithms will be tested to achieve a better localization error.

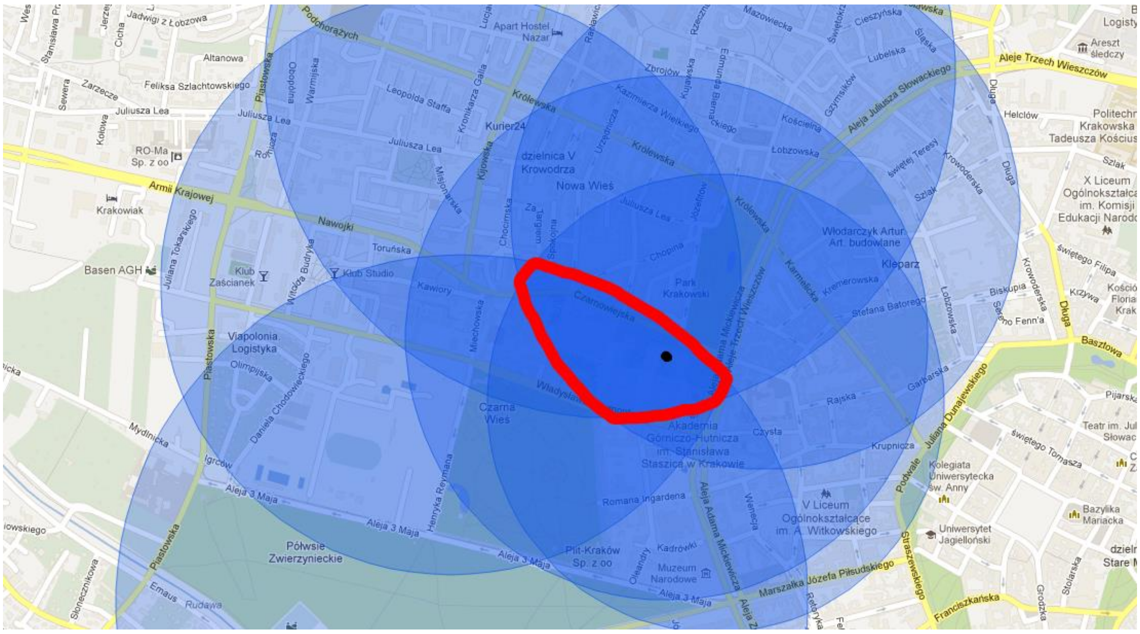

Figure 7.3. *GSM* base stations locations in the nearest area and real device position

A localization error is highly related to a localization technique. When a *GSM* network is used for a localization, the error can be up to several km in rural areas. In large cities the error can be less than 100 m. A *GPS* localization error depends on weather conditions, a nearby buildings layout and a *GPS* receiver capabilities, etc. and it can be less than 3 m (excluding *GPS* devices for military purposes). Regardless of the localization technique, when it comes to a navigation system, the localization data should be taken as guides in localization rather than actual strict navigation commands for blind people.

3D laser scanner for obstacle recognition

Since the Kinect device has some technology issues that disqualify it from using in high reliability safety systems for blind people, for instance narrow scan angles, another system was tested – *3D* laser range finder cooperating with camera feed. Basic principles of *3D* laser range finder operation are mentioned in CHAPTER 4.

SYSTEM OVERVIEW

The system block diagram is presented in Figure 7.4. As the main device that collects the data the *2D* optical laser range finder was selected. It supports both *USB* and *RS232* interfaces. The Hokuyo laser range finders are available in many models. They differ in measurement resolutions, the maximum range, packages, etc. The one that is used in the system has a maximum range of over 4 m and 240° angle of sight. The device measures distances to nearest points for each angular step in real-time. This gives the *2D* distance map of the specific plane in the polar coordinate system. To acquire a *3D* distance map the servomechanism was implemented to allow the laser beam to work in the third dimension. The laser range finder scans the first plane, then it is rotated with the given angle and it scans the next plane. This sequence continues until the rotation angle reaches the value of 180°. Since the scanning device gives the *2D* distance map of the specific plane and the rotation angle is also known, one is able to create the *3D* distance map of the surrounding.

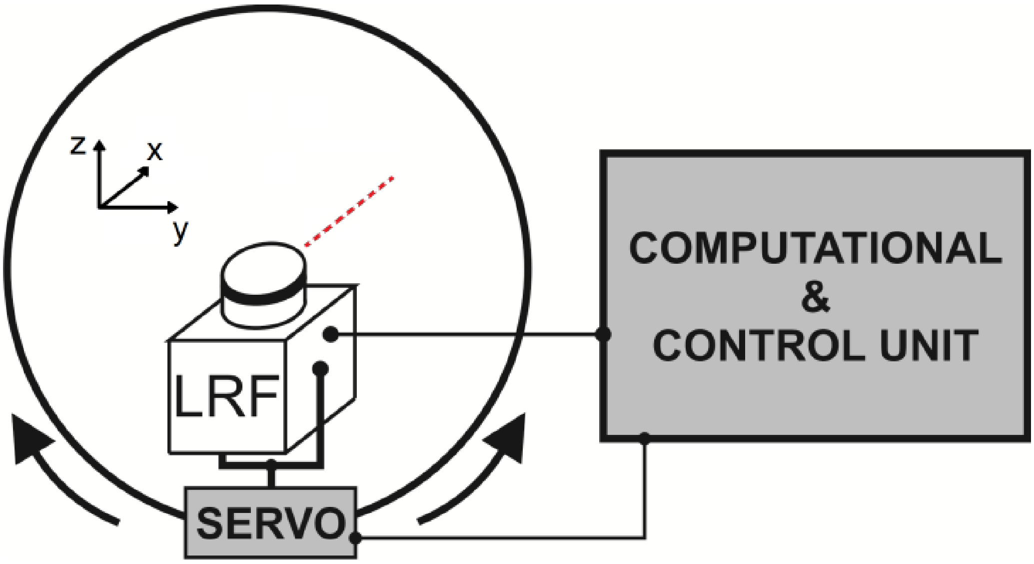

Figure 7.4. System block diagram

The rapid development of *ARM* microprocessors and *FPGA* chips over the past years has made it now possible to build relatively small devices with ability to handle computations for video streams in real-time. There is no need for blind people who use devices with ability to recognize objects in a video feed or in a *3D* distance model to carry heavy computers in their backpacks like they used to [Ued06]. For testing purposes and a rapid development of system algorithms, the MATLAB software was used.

TEST SCENARIO

A testing scenario has been created to show the main advantages of using both the video image and the *3D* distance map in one device. The test area is within a room. Its image is presented in Figure 7.5. There are objects of basic but different shapes, sizes and colors. They are located in different distances from the laser range finder. Their tilts are also not equal. This helps to show extended functionality with detecting different surfaces, their shaper, differentiate with a help of colors, etc. Chairs are of irregular shapes, so they are good for testing algorithms for errors. There is also a black suitcase and a piece of glass between chairs to test the infrared ranging capabilities. All the objects are situated in the room which means it is a closed space with walls, a roof and floor. Information about dimensions of a room is as important as information about objects in the room for a blind person. There are also two windows.

Figure 7.5. Test scenario photo

The Hokuyo laser range finder (URG-04LX model) is intended for low range applications, usually with measurements not more than 4 m. The angular resolution is 0,36° with the maximum view angle of 240°. The accuracy is ±10 mm and ±1 % for measured distances of 20-1000 mm and 1000-4000 mm respectively. Whereas, the resolution of measurements is 1 mm. The Hokuyo laser range finder uses the laser beam phase shift to calculate the distances.

The use of this laser range finder provides resolution and accuracy good enough to be built in devices for blind people. A higher resolution and range would increase the power drain.

DATA PROCESSING

Data from the laser range finder is acquired via the *USB* interface. Every plane is scanned 10 times and then for every angle the median value of the data is calculated to minimize any errors. As soon as all the data is transferred, a model is being created. Due to the fact that acquired data points from each *2D* plane are in the polar coordinate system and the rotation angle of the whole sensing device is also known, the initial *3D* model is also in the polar coordinate system. The created model is to be related with the corresponding image from the camera mainly for detecting objects purposes. Usually, the primarily desired information for blind people relates to the obstacle presence in the specific range to help to avoid it if necessary and then the obstacle recognition. For that reason and also for a simpler model-image pairing, points coordinates are being recalculated to the *3D* Cartesian coordinate system. A *3D* visualization of the test scenario with the corresponding image is presented in Figure 7.6.

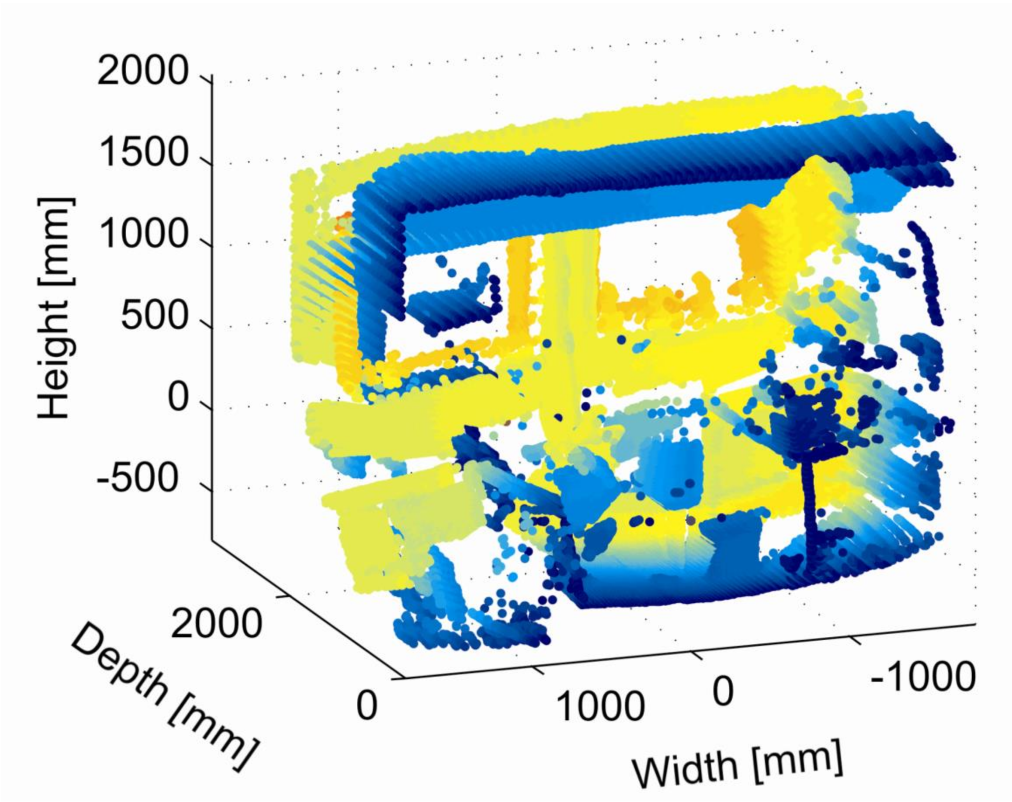

Figure 7.6. *3D* distance model of the test scenario created with a laser range finder

The data points are stored in a *X*, *Y*, *Z* coordinate fashion way instead of a coordinate matrix thanks to which, the calculations and model transformations take less time and also less data memory is used. Additionally, another advantage of this method is that there is a quick way to narrow down the *3D* laser range finder view limits by software. This is helpful to focus on possibly important objects. In Figure 7.7 there is the *3D* model view of the test scenario with limited boundaries presented. This accelerates computations.

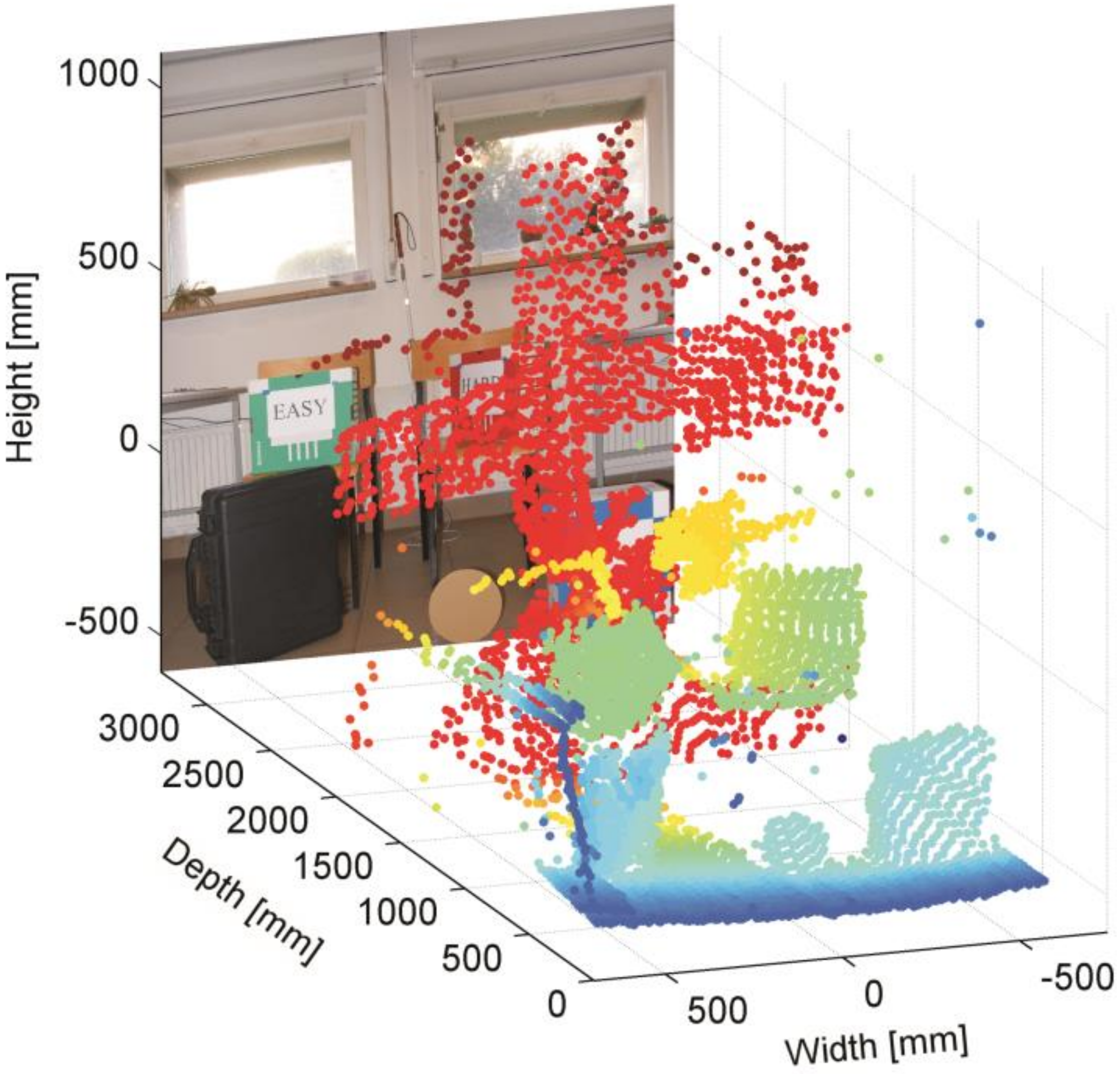

Figure 7.7. Test scenario photo with the corresponding part of the *3D* distance model

TESTS AND RESULTS

Test were performed at the test scenario. The scenario and its *3D* model created with the laser range finder are presented in Figure 7.7.

To help blind people with a safe navigation, objects and surfaces detection is a must. This is a primary function of all navigation aids for visually impaired people. Some of the scenario objects surfaces are almost normal to the ground level and at the same time parallel to the scanner surface, for example, the blue and white box, the green and white box, the brown paper circle. Figure 7.8 helps to illustrate this layout description. To detect those surfaces the device checks all the data points which have similar *X* coordinate value (depth). Whenever there is a group of data points accumulated in some area, those specific data points are allegedly considered a surface and they are passed for further processing. The visualization of this method is presented in Figure 7.9 and the result of detecting the blue and white box, the brown paper circle and some part of the black suitcase is presented in Figure 7.10(a) as the plane with the data points from the laser range finder.

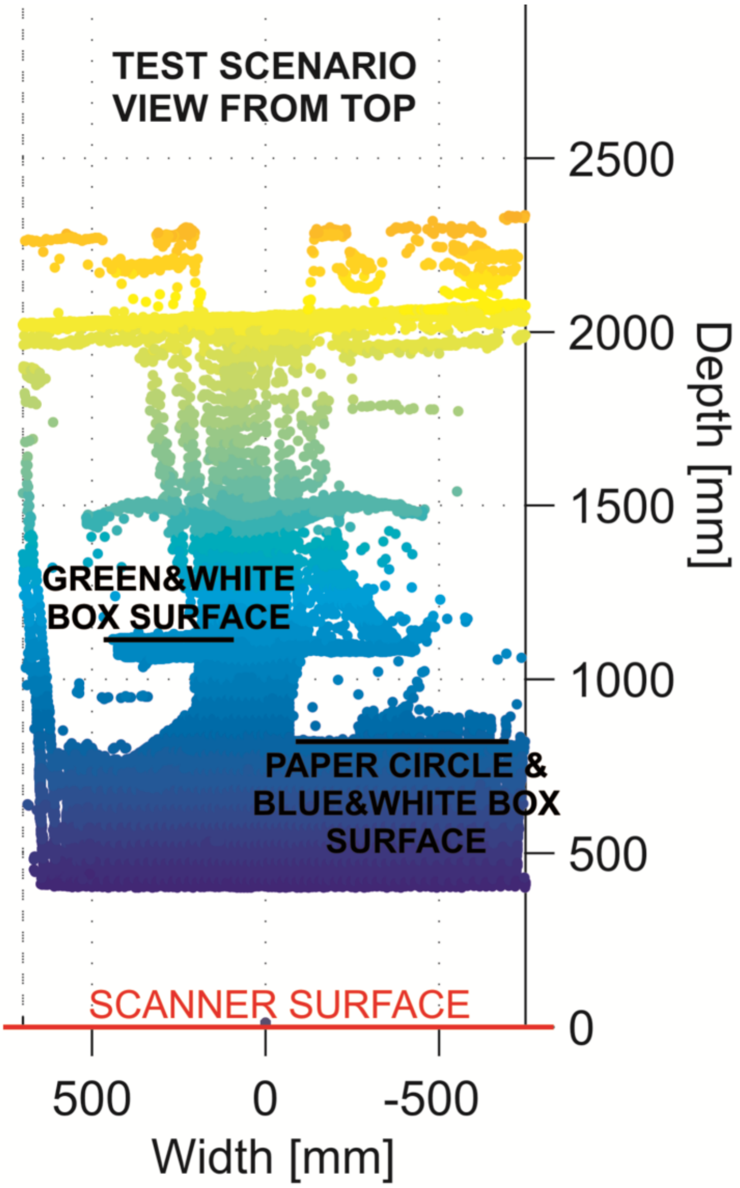

Figure 7.8. Top view of the *3D* distance model with marked surfaces which are normal to the ground level and at the same time parallel to the scanner surface

The distance from the plane to the scanner is approximately 80 cm. It is hard for a computer or other device to recognize a shape or even a continuous surface from those points. That is why the preprocessing had to be implemented. The process checks if there are other data points inside every point proximity of a configurable size. If the amount of points in the neighborhood exceeds the set value, the algorithm fills the proximity as it was a solid surface. After the preprocessing the plane from Figure 7.10(a) the result is shown in Figure 7.10(b). Now the plane from the model is more suitable for image processing algorithms. Thanks to the preprocessing the segmentation of this image is more reliable. The binary form of the preprocessed plane is ideal for a shape recognition or even a shape smoothing. With a use of the image from the laser range finder the shape recognition of objects is possible without the image processing from the camera.

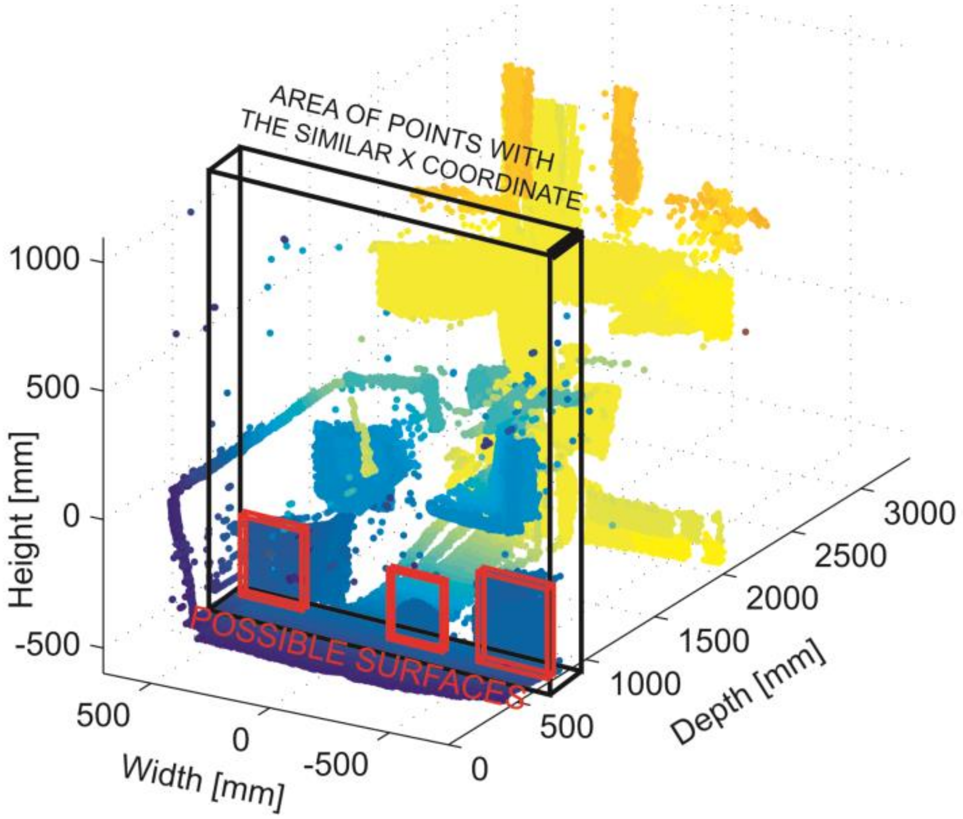

Figure 7.9. 3D distance model with marked area which has points with a similar *X* coordinate value. In this area there are groups of data points which could be solid surfaces

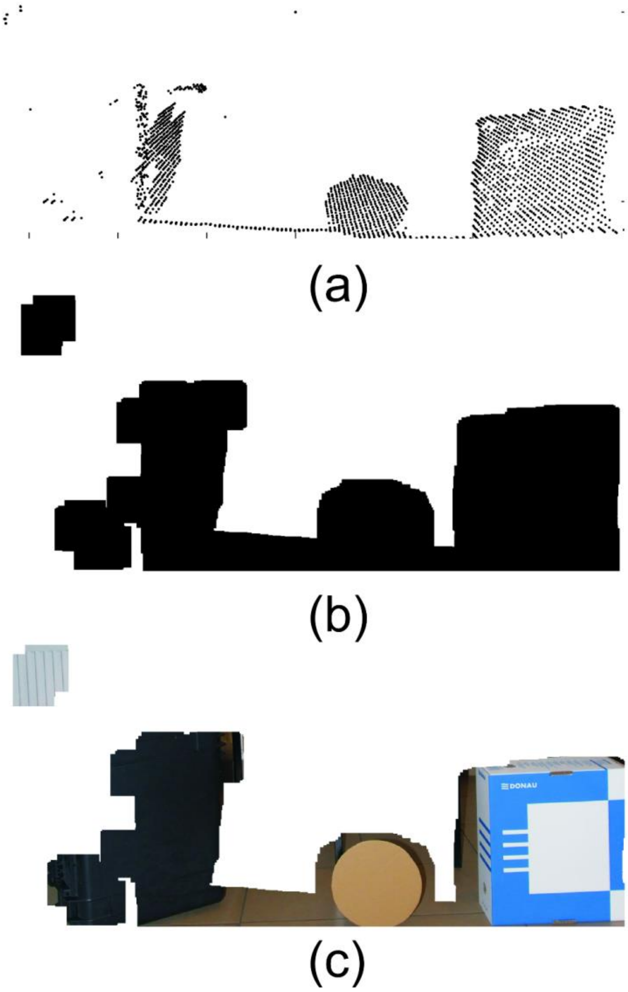

Figure 7.10. Results of detecting surfaces of the blue and white box and the paper circle:
(a) Data points gathered from the laser range finder
(b) Preprocessed data points. Algorithms for a shapes recognition work better on solid surfaces than on data points
(c) Result of masking the photo of the test scenario with the preprocessed data points surface

Furthermore, due to the fact that the *3D* model of the test scenario is available, detected objects dimensions and their distances from the scanner could be easily calculated. The object detection and shape recognition are very important for blind people, however not sufficient enough for a highly reliable safety system in case of navigation. If a rectangular object is detected, it can be, for instance, a simple box, a suitcase, or even a *LCD* display. Distinguishing objects with similar shapes and sizes is also very important for visually impaired people. This is where an image from a video camera becomes handy. With the image the algorithms are able to check objects colors, recognize faces, compare the object with the database and recognize the object. However, it is redundant to check the whole image. Usually, the far background is not important for blind people. The algorithms should be focusing on objects which are in a close range. It is hard to perform that only with feed from camera. Processing only selected, important pieces of the image from the camera can be achieved by combining the image with the *3D* scenario model. To crop parts of the image which contain the blue and white box, the brown paper circle and some part of the black suitcase, the preprocessed plane from Figure 7.10(b) can be used as a mask. Before the mask can be applied on the image, some scaling operation must be applied. The whole *3D* model created from the laser range scanner is in scale. This means that the same object located closer and further from the scanner has the same dimensions in the model. This does not apply in pictures. In pictures, likewise people see an environment, an object in distance looks smaller then if it was closer to an observer or a camera. A dimension reduction value depends on a type and parameters of the used lens. Taking into account the distance from the selected plane to the scanner, it is possible to mask the scenario picture with the scaled preprocessed plane from Figure 7.10(b). The masking result is presented in Figure 7.10(c). Since the green and white box is also almost normal to the ground level and at the same time parallel to the scanner surface, it is marked as possible surface. The results of the described processing are presented in Figure 7.11.

The front surfaces of the black suitcase and the red and white box in the picture are inclined in regard to the scanner surface. Thanks to the created *3D* model it is possible to use the same algorithms which were used for detecting parallel surfaces in detecting inclined ones. Thanks to the fact that the data points are stored in a X, Y, Z coordinate way, rotating the whole *3D* model around some axis is possible by multiplying other axes by a rotation matrix G (20):

$$G = \begin{bmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{bmatrix} \quad (20)$$

where β is a rotation angle.

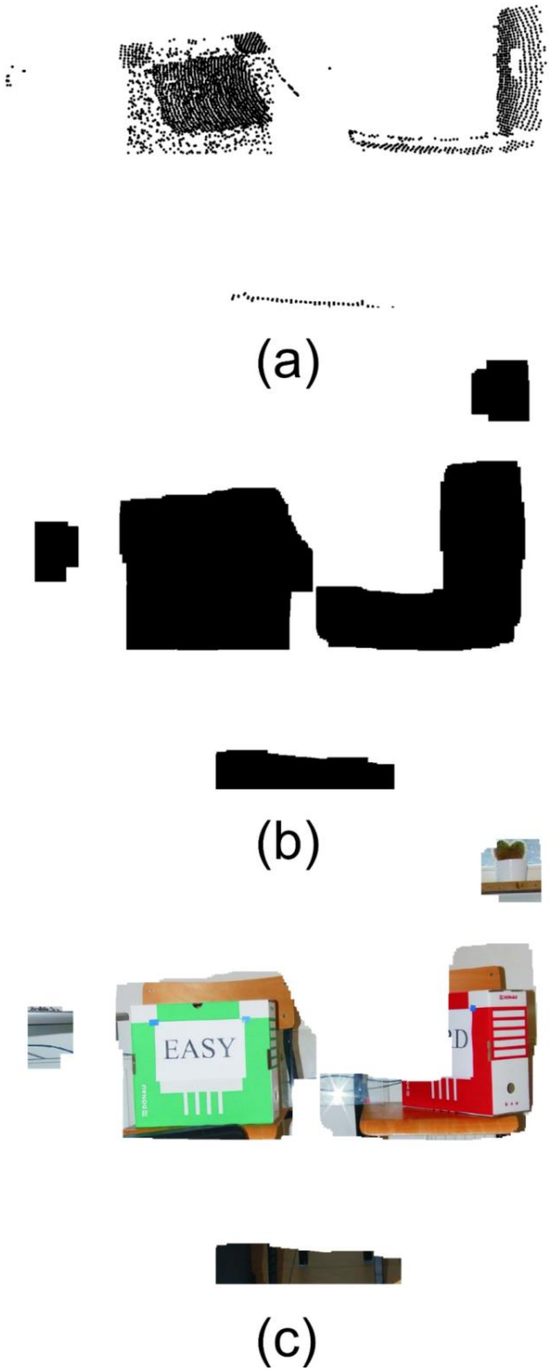

Figure 7.11. Results of detecting the surface of the green and white box:
(a) Data points gathered from the laser range finder
(b) Preprocessed data points. Algorithms for a shapes recognition work better on solid surfaces than on data points
(c) Result of masking the photo of the test scenario with the preprocessed data points surface

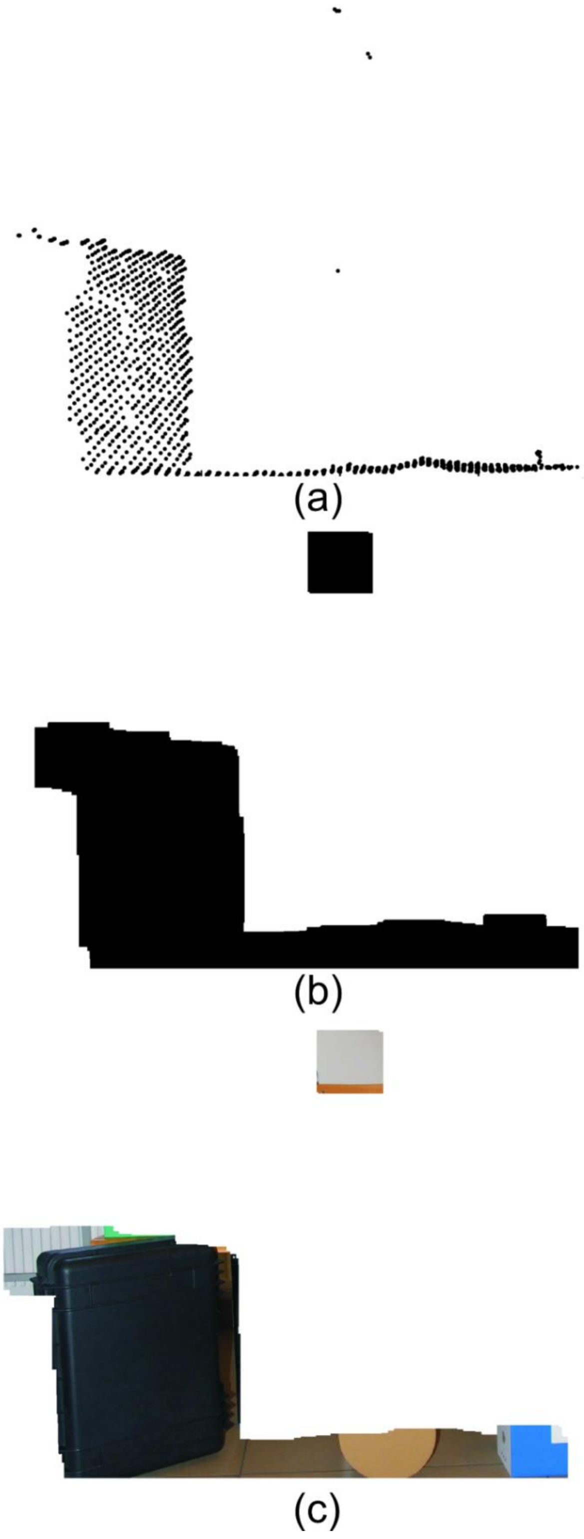

Figure 7.12. Results of detecting surface of the black suitcase:
(a) Data points gathered from the laser range finder
(b) Preprocessed data points. Algorithms for a shapes recognition work better on solid surfaces than on data points
(c) Result of masking the photo of the test scenario with the preprocessed data points surface

The results of detecting the inclined surface of the black suitcase, preprocessing the plane and masking the picture with it are presented in Figure 7.12.

Another important information for blind people is a height of a room. Once again thanks to the *X*, *Y*, *Z* coordinate data points storage, it is possible to calculate the position of a floor and a ceiling regards to the scanner. It is done by finding two *Z*-coordinates, one positive (above the scanner) and one negative (below the scanner), with the biggest number of points. The sum of absolute values of these two *Z*-coordinates gives the room height. The test scenario room positive and negative *Z*-coordinates were 201 cm and -62 cm accordingly.

The laser range finder scanner has a problem with detecting glass, which is transparent for the light. That is why the piece of glass between chairs is not visible in the *3D* model. For windows detecting algorithms this feature can be useful. If there are large blank rectangular shapes on a solid plane that could indicate that in that particular place there is a wall with windows. However, for blind people this feature in navigational systems could be deceptive and likely to be dangerous, for instance a closed glass door could be taken as an open door or a door-frame without a door. There is no difference between a clean glass in a window and an empty space. Those could lead to a confusing and possibly dangerous navigation of blind people.

CONCLUSIONS

The tests have proved that the highly reliable safety navigation system for blind people can be based on the camera and the laser range finder, working mutually. Both basic and complex functions can be implemented. Not only obstacles and shaped detection works correctly, but also the system is able to calculate with high accuracy the objects dimensions and the distance between the user and the object. It is useful for creating indications in navigation systems. Storing the *3D* model data points in *X*, *Y*, *Z* fashion way makes it easier for algorithms to operate, for instance, cropping the whole model or some part of it, rotating, image processing, etc. Additionally, it consumes less memory.

The main advantages this solution has over the usage of only laser range finder for modeling the environment are the possibilities of image processing from the camera feed. Thanks to this feature objects recognition can be based not only on dimensions but on a physical appearance, color and texture is available, not to mention all the algorithms associated with a computer vision, for instance, face detection, objects following, etc. As for the advantages over a navigation system for blind people based on stereoscopic image from two cameras only, the proposed system is able to maintain its basic functionality like, the object detection, calculating distances to the objects and informing about them, whenever it is used in very dark rooms where systems based only on cameras fail due to the insufficient light level.

CHAPTER 8: PROTOTYPE, TESTS AND RESULTS

This chapter presents the prototype of the device for detecting and informing about dangerous obstacles which are present on the blind person path and also, hazardous holes or small objects that are laying on the ground.

Trials have been performed with the participation of blind and visually impaired people from the Special Educational Centre for Blind and Visually Impaired People in Kraków. Teachers from that center watched over the safety of the testers and also provided vital guidelines for the test scenarios.

Prototype of the device

The prototype consists of 4 subsystems: multichannel ultrasonic driver, *IRRF* with stabilization, 6-point vibration bracelet for signaling and power management unit. The system block diagram is presented in Figure 8.1.

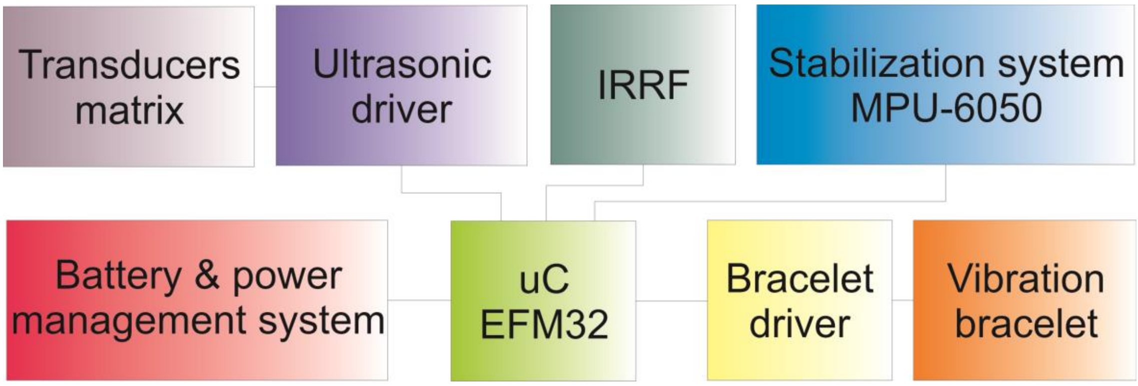

Figure 8.1. Prototype block diagram

The whole system is powered with *Li-Pol* rechargeable battery. The energy consumption was optimized in a way that the system is able to withstand the whole day operation time without charging. The charging process was designed to be simple and convenient for blind people. One only has to plug in the cable with 5 V (i.e. from *USB*) and all the charging functionality (current limit, low current when starting up and when battery is fully drained, thermal switch off) is taken care of by a microcontroller.

Since there are many voltage domains needed for the subsystems, multiple *DC/DC* voltage converters were used. All the voltages are considered low voltage, therefore the risk of dangerous electrocution is minimized. During the process of designing the prototype and creating firmware, strong focus was on low energy consumption. So, the used components have low overall current consumption and propped energy modes were used.

The multichannel ultrasonic subsystem is used to drive six transducers that can provide information for distance measurements in various angles, so larger area can be scanned for objects near blind users. The driver was designed as a separate *PCB*, so its integration was less time consuming. The communication between the driver and microcontroller is realized with *I/O* pins. It that way, every ultrasonic transducer can be accessed independently. The real image of the driver is presented in Figure 8.2.

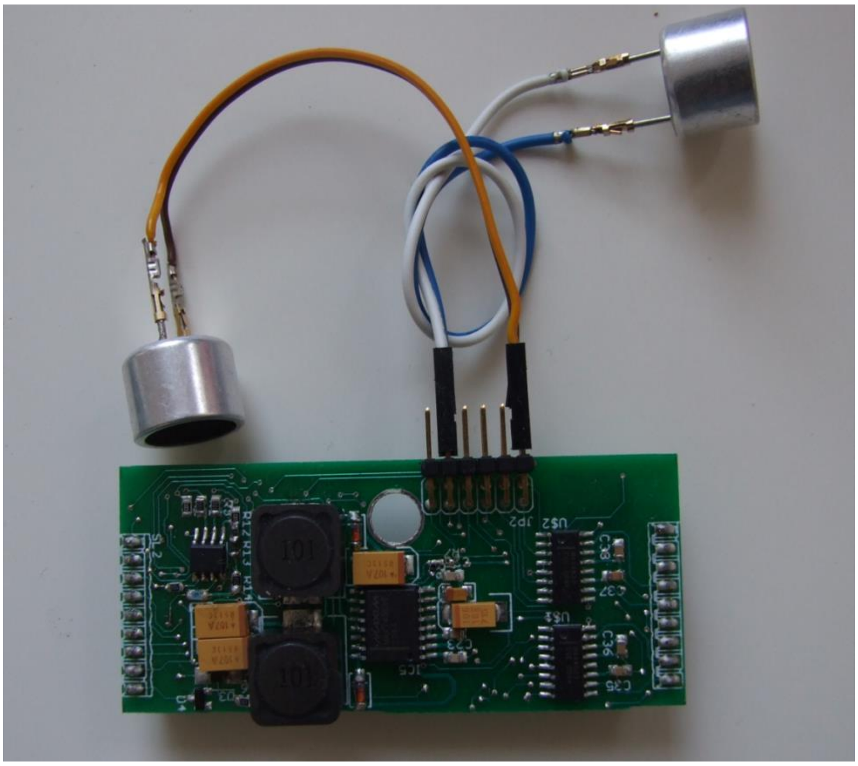

Figure 8.2. Photo of the multichannel ultrasonic transducers driver

The *IRRF* module used in the prototype in order to scan for ground imperfections and objects of interest is Sharp *GP2Y0A710K0F*. To obtain acceleration data the *MPU-6050* chip was used. This particular chip provides not only the data from built-in accelerometer and gyroscope, but also services for computing other, motion related data, for example, linear acceleration in world format. Thus, the microcontroller computational time can be optimized in order to save energy. The real image of the *IRRF* and the *MPU-6050* chip is presented in Figure 8.3.

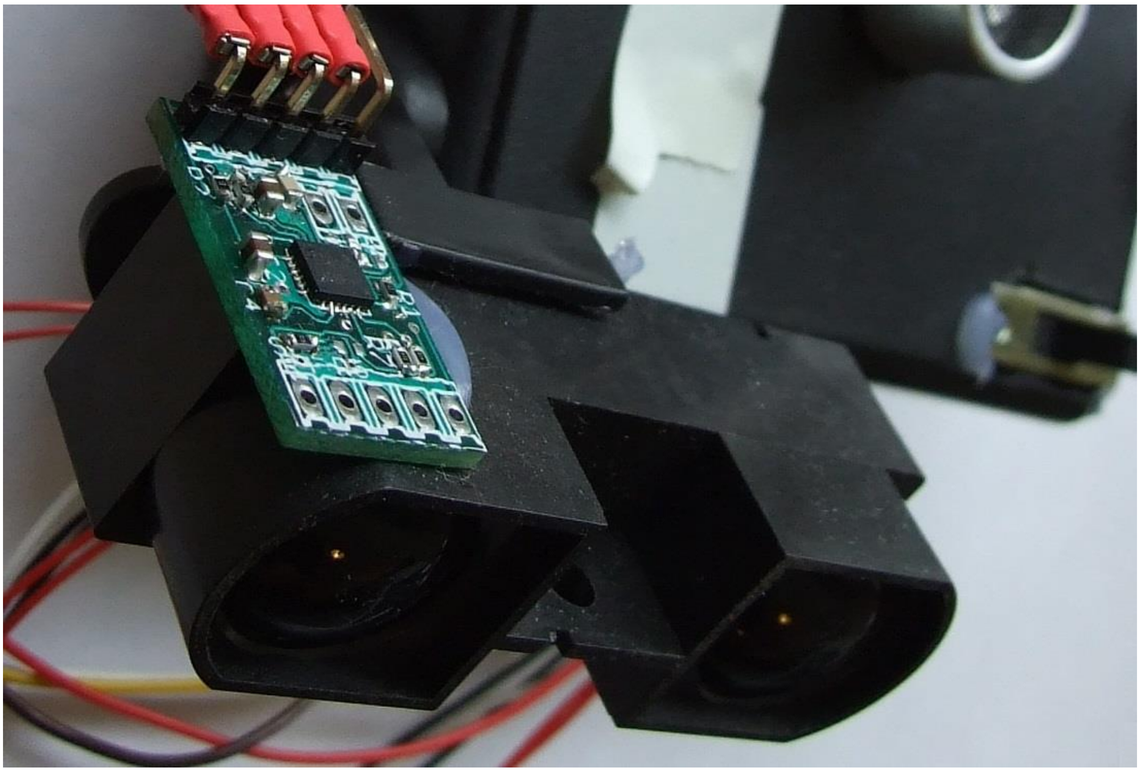

Figure 8.3. Photo of the *IRRF* and the *MPU-6050* chip

For signaling detection of obstacles and transmitting information in a way that the hearing sense would not be disturbed, a 6-point vibration bracelet with driver was added to the prototype. Vibration points are small vibration motors widely used, for instance, in mobile phones. The bracelet itself was constructed to match wide range of users' wrists sizes.

The driver can operate both as integral part of the prototype or an independent device. The latter is useful for teaching blind people vibration signaling schemes and getting to know the bracelet itself. Plus, the driver can be used in other devices, not only in the presented prototype. The driver can be battery operated (it has its own battery charger and power management unit) or it can be supplied with power from the prototype power domain. The 6-point vibration bracelet is presented in Figure 8.4.

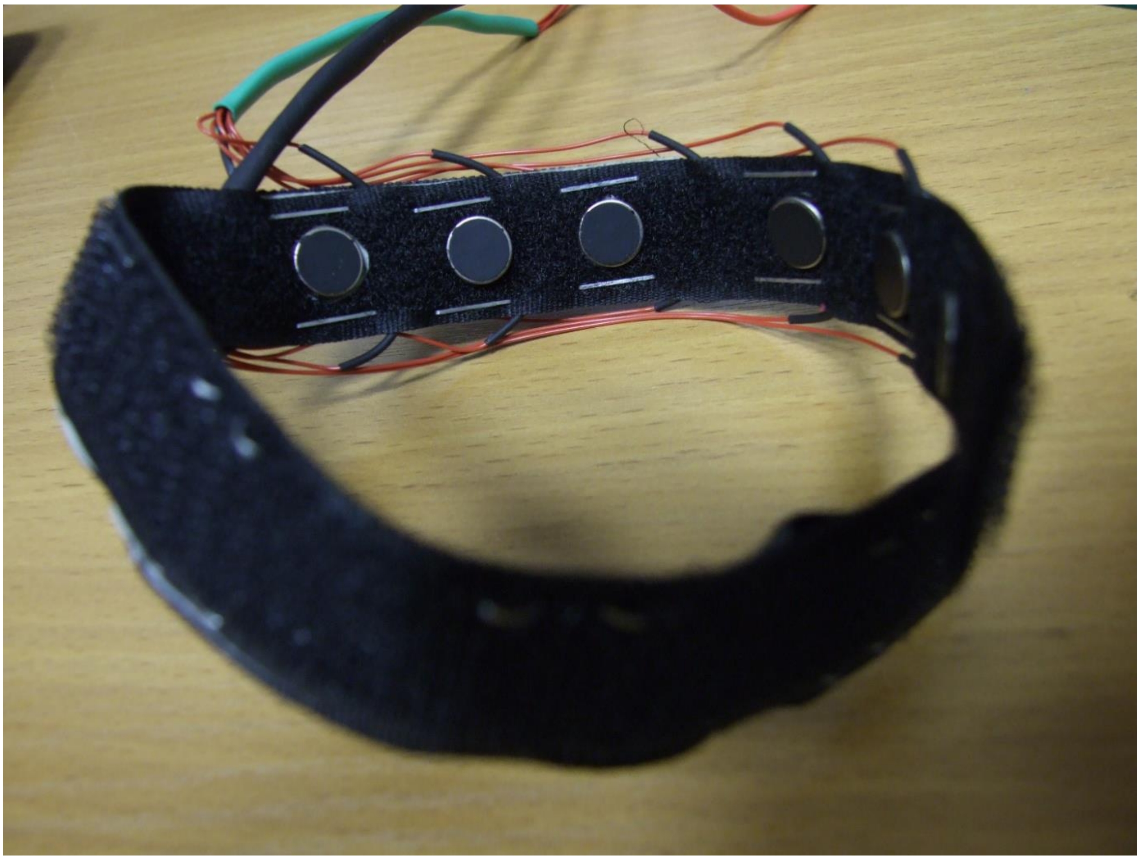

Figure 8.4. Photo of the 6-point vibration bracelet

The subsystems were enclosed in a plastic casing with a clip. Users that were testing the device wore a technical suspenders and with this clip the prototype was firmly attached to the testers' chests.

Learning period

The prototype was tested among 8 blind children and 1 visually impaired child from the Special Educational Centre for Blind and Visual Impaired People in Kraków. They all were between 12 and 15 years old. In order for them to get used to the device and not to affect their study time at school, the tests were split into a couple of separate sessions.

The first session was conducted in a way to interest the kids with the device and describe its functionality. Children were told what this device measure, how it is done, what are the sensors and other basic information. Everyone could touch the device and manually investigate it – the casing, sensors, *PCB*, vibrating points, etc. Children were very enthusiastic about the device and asked a lot of questions, in regards to how it has been built. All the children wore the device for the first time.

The second session was conducted in order to get the kids used to vibrating bracelet and to teach them the basic signaling methods, schemes. Firstly, the vibration bracelet was fitted to the wrist – not too loose, but also not too tight to cause discomfort. Then, the vibration signal in one point started with a minimum strength. The strength was being increased up to the point when the blind used was not able to recognize the change. In that way the minimal and maximal vibration signal recognition levels were set. Afterwards, various points were vibrating and the perception for the location of the points were checked. It was observed that blind and visual impaired people have better perception ability, regarding tactile signals, than the people with unimpaired vision. In the end of this session, some simple vibration schemes were introduced to the children: multiple vibration impulses, rotating vibration, etc.

After the kids were familiarized with the prototype and the bracelet and also learned how to recognize and interpret the vibrations signals, the sessions with scenarios tests were conducted. In those sessions testers were dealing with real objects that are commonly present in average day scenarios.

Test scenarios

Since test sessions took place in the building to provide a better safety environment, it was hard to find holes in the ground for testing. Thus, some dangerous obstacles, i.e. holes of differ sizes, were created using paper boxes.

HOLES AND OBJECTS ON THE GROUND

The teachers from the school suggested that a hole with similar dimensions like curb would be the perfect obstacle to detect in tests. That is why a 10 cm high hole was 'constructed' and its detection was tested with a help of the blind people. They had to walk towards it and without knowing where it exactly was, they were to stop when the bracelet would signal the hole. All the data was being stored on the *SD* card for future analysis.

At first the kids were walking really slowly with only a little confidence. A slow walk works for advantage in the filtration process, so the detection and signal was always correct and immediate. One of the data visualization of this scenario is presented in Figure 8.5. For better visual results, the *R* values have a constant added to match the level of *D* values on the chart.

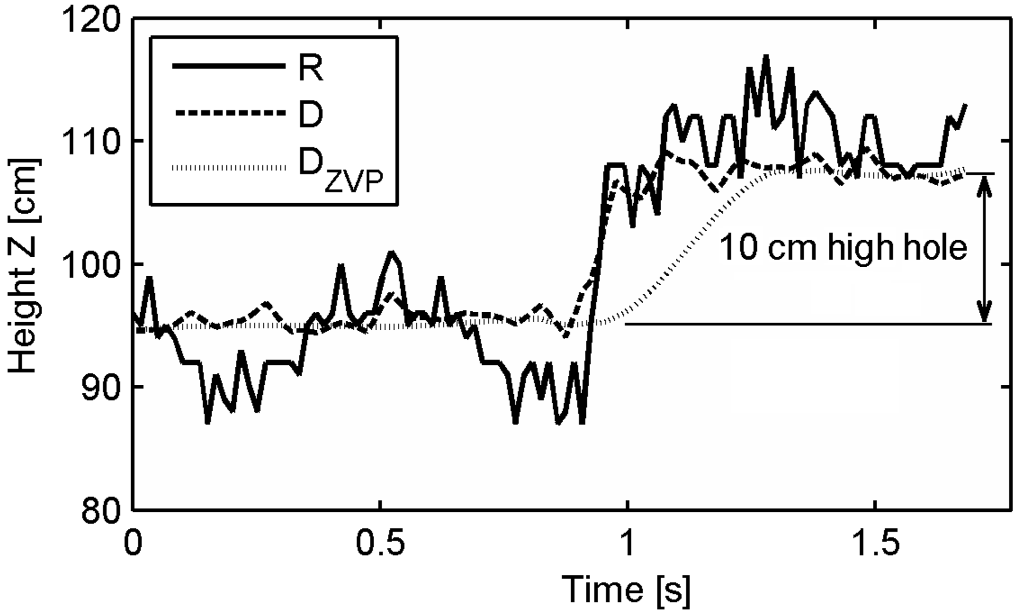

Figure 8.5. Filtration data in a scenario of detection 10 cm hole

Other holes sizes were also tested. The more tests kids took, the more confident they felt using the device. The data visualization of the correct 7 cm high hole recognition is presented in Figure 8.6.

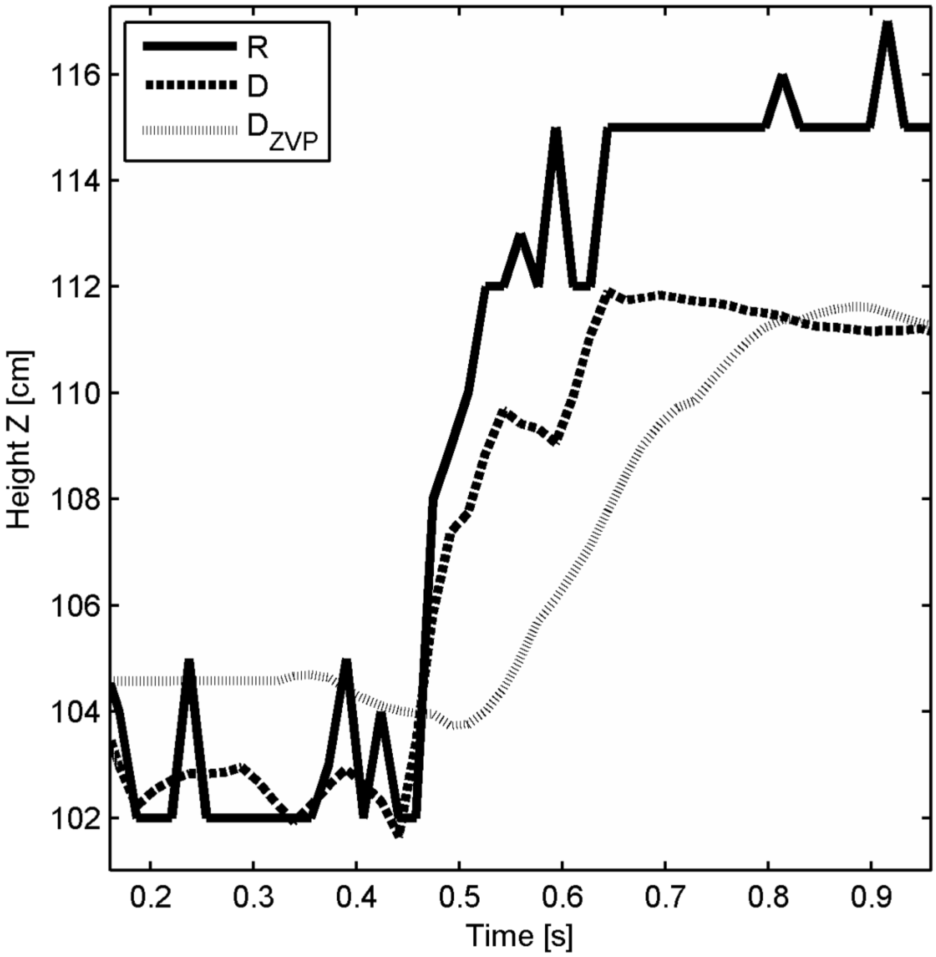

Figure 8.6. Filtration data in a scenario of detection 7 cm hole

The second group of dangerous obstacles suggested by teachers included both small objects (for example curbs) and bigger objects which could injure knees, like barriers and shops' advertisements.

Firstly, the 13 cm high paper box was placed on the blind users' path. All the testers have no problems with detecting the obstacle at least one step in front of them. The data visualization of the correct 13 cm high object recognition is presented in Figure 8.7.

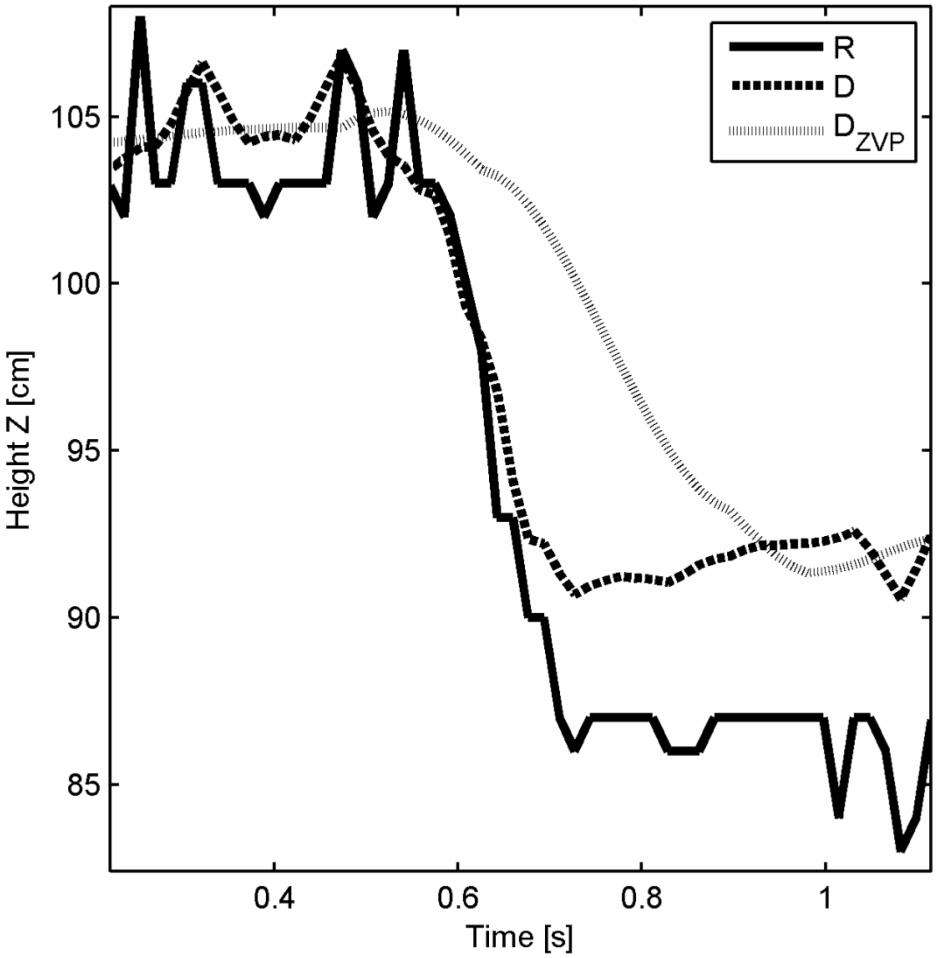

Figure 8.7. Filtration data in a scenario of detection 13 cm object

For testing bigger obstacles, an irregular shaped object – a wooden chair was used. Those kinds of obstacles are the common reason that blind people trip over in both familiar and unfamiliar places.

STAIRS

Another common obstacles that appear on everyday basis on the blind people paths are stairs, both going up and down. Thus, these obstacles were also tested for detection with a help of blind users. To assure safety, when users were too close to stairs, they were assisted or warned by voice.

When the user's device beam meets the first stair (going up), the readings will decrease by the stair height. After that the readings should stay at the same level until the beam meets the second stair (if the second stair is not detected, the object should be signaled as some normal obstacle laying on the ground). In the moment that the user reaches the stairs and starts to go up, the readings should oscillate at the constant level, because both the device and the beam ending are increasing the height position relative to the ground. At some point, the beam meets the last stair and from that point the readings increase, because in every step the device position increases the height relative to the level of the last stair. When the user reaches the final step, the readings stay at a constant level.

One tester's data visualization of this scenario is presented in Figure 8.8.

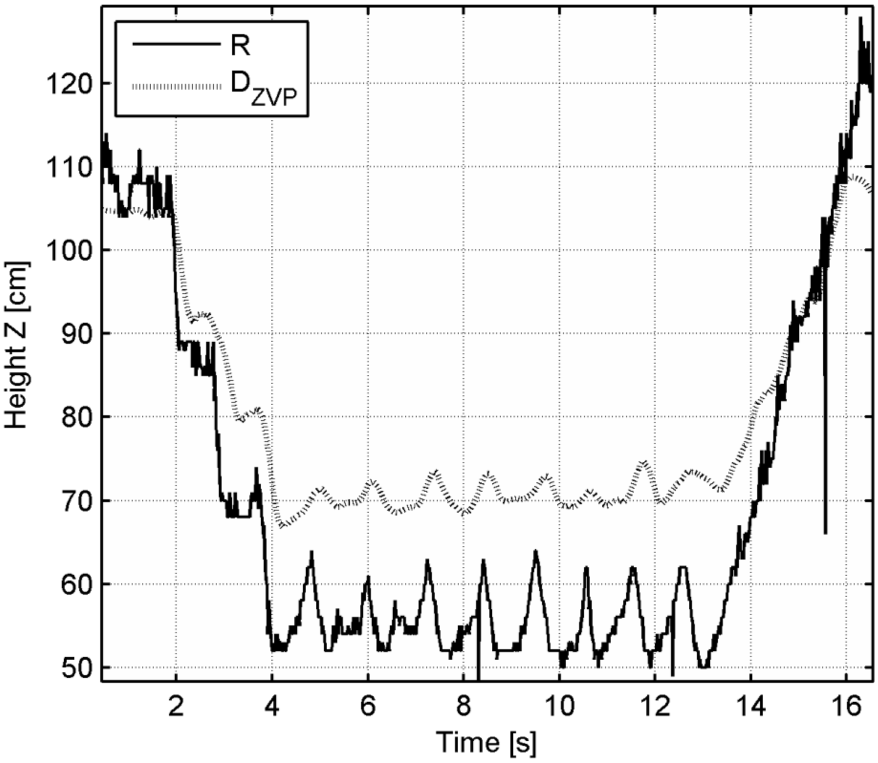

Figure 8.8. Filtration data in a scenario of walking upstairs

By analogy when the user's device beam meets the first stair (going down), the readings will increase by the stair height. After that the readings should stay at the same level until the beam meets the second stair (if the second stair is not detected, the object should be signaled as some hole in the ground). In the moment that the user reaches the stairs and starts to go down, the readings should oscillate at the constant level, because both the device and the beam ending are decreasing the height position relative to the ground (end of stairs). At some point, the beam meets the end of stairs and from that point the readings decrease, because in every step the device position decreases the height relative to the level of the end of the stairs. When the user reaches the last step, the readings stay at a constant level.

One tester's data visualization of this scenario is presented in Figure 8.9.

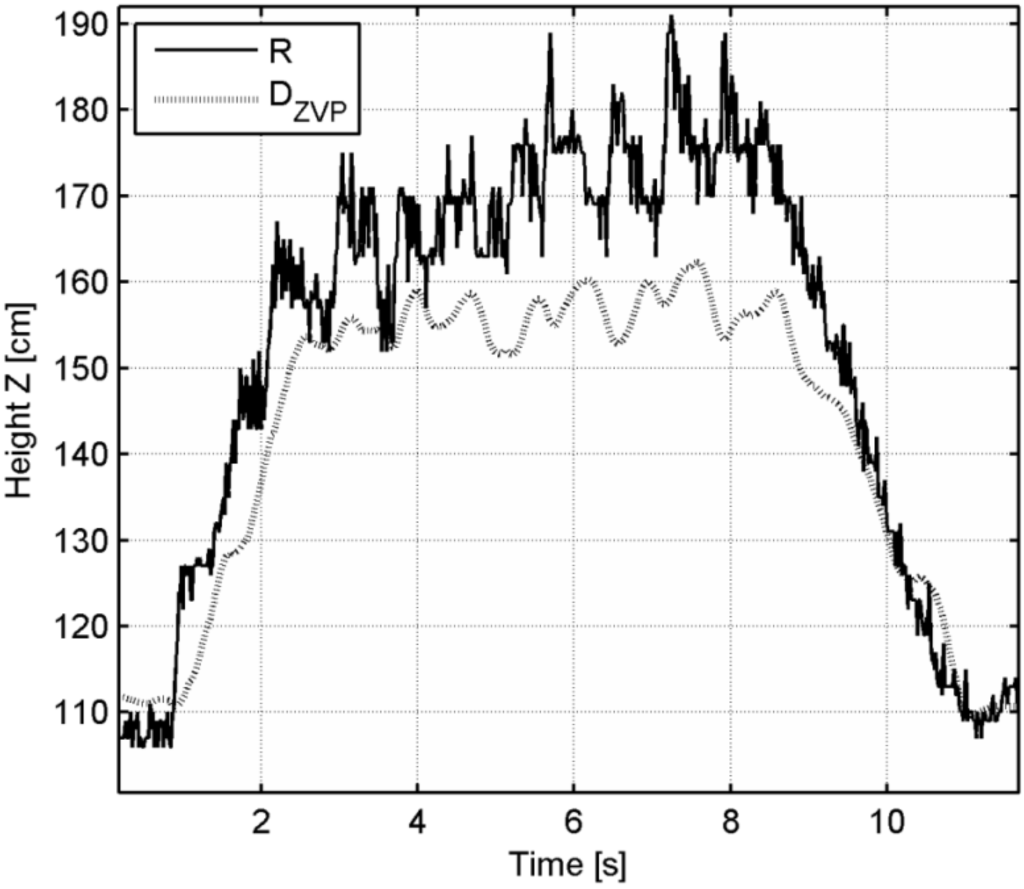

Figure 8.9. Filtration data in a scenario of walking downstairs

With a method of local maxims the amount of stairs can be detected and this information can be sent to the user with vibrations. The end of stairs can also be detected and the user can be informed that the stairs will end in 2 steps.

Figure 8.10 presents the detected stairs with a peak-finder method.

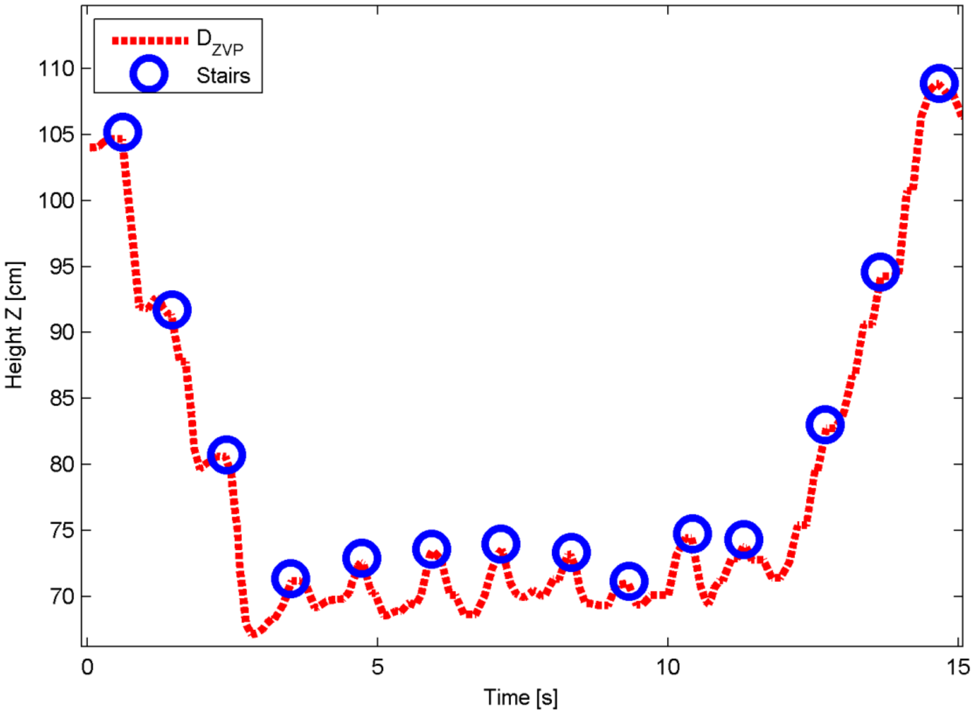

Figure 8.10. Detected stairs with a peak-finder method

Figure 8.11 presents of the children testing the stairs detection.

Figure 8.11. Child testing detection of stairs going down

WALLS AND ROOMS' GEOMETRY

Tests also included detection of walls, thus geometry of the room, and other objects in front of blind users. At first, only one ultrasonic transducer was activated to help users to accommodate. Testers had to navigate through the corridor and avoid impact with the obstacles, which they did successfully. The interesting part, which was not expected in the scenario, was that one door was opened and with help of the device the users were able to locate this open door, which they have found very helpful.

Besides the static elements, like walls and obstacles, the tests included detecting moving obstacles – other people. With different scenarios – people crossing testers' path, walking towards and recede – testers were able to locate the moving obstacle and react on time.

Figure 8.12 shows one tester detecting the distance between him and the wall.

Figure 8.12. Child testing detection of walls and distances

Results and observations

Thanks to dividing the tests into the familiarizing phase, the learning phase and real-life tests phase, the results look promising. Also, short sessions and teachers' advice helped to increase the efficiency and keep the children focused and interested during the tests.

All the kids have successfully completed scenario tasks and recognized the signaling objects. In the test group one child was not entirely blind, but he has a significant visual impairment. Thus, to normalize the group, this child was blindfolded throughout the tests – that was the teacher's suggestion.

The signaling schemes were as follows: hole or stairs going down – three short vibration impulses; small object on the floor or stairs going up – two short vibration impulses; objects being on the belt and above level – constant vibrations where the vibration strength was coded accordingly to the distance between user and obstacle. The phenomenon was that some children pointed out that with the change in vibration strength when they were moving towards the wall, they could 'feel the distance'. They stated that it was fascinating for them and certainly useful in real life scenarios. The lack of vision, thus the inability to measure the distance to the obstacle, could be compensated with the sense of vibrations. The other interesting observation was the mentioned ability to find the open door in the corridor, which is also useful in everyday scenarios.

The children also stated that they would feel safer having this kind of electronic aid, so they could remotely sense the obstacles and minimize the risk of bumping into objects or tripping over objects and falling into holes. Having in mind the known prices for some devices for blind people, they were also concerned about the price of this device.

Custom casing

During preliminary consultations after some technical tests and also trials with blind and visually impaired people from the Special Educational Centre for Blind and Visual Impaired People in Kraków, the idea of creating a custom casing came to mind. Basically, it was caused by the fact that most of the generic casings do not satisfy requirements of blind people *EA* needs. It is not because the generic casings do not meet some electronics and safety regulations, but it is simply because of the subjective opinions from blind and visually impaired people society. The result of the consultations is that blind people would not want to wear a brick-sized devices with sensors attached in a way that these sensors could be damaged by a physical impact with a hand or some wall. It would be discomforting for them. Additionally, this factor is a social one, and the size and shape of the casing should be ideally carved to the size of the electronic components and sensors – having in mind, not to influence the functionality of the device itself.

The custom casing idea was also the result of destruction of some sensors after children were getting familiarized with the device. Since they have been very enthusiastic and curious about the device, they extensively study the shave of the device by touching it. This leaded to the mentioned damage of the mechanical joints.

Manufacturing the mold for plastic injection technique for creating casings for a prototype generates relatively high costs. Not to mention that almost always some changes have to be done in the design process. Therefore, *3D* printing seems ideal for creating first designs and sample custom casings.

The *3D* printer used manufacture the prototype casing was MakerBot Replicator 2. It is a single extruder device with a 28,5(L)x15,3(W)x15,5(H) cm build space. It can print with 1,75 mm diameter filament material. The quality of a print can be set and the best achievable resolution is 100 μm (a layer resolution). The print models can be created with many *CAD* software, as long as the models can be saved or converted in a *STL* format.

With that solution one can create suited casing design, correct design errors, make changes based on blind people suggestions and tweak the inside of the casing to meet any changes in *PCB* and sensors shapes. This can be done with a very short time span and with a low costs, comparing to manufacturing prototype mold.

The preliminary casing design is presented in Figure 8.13.

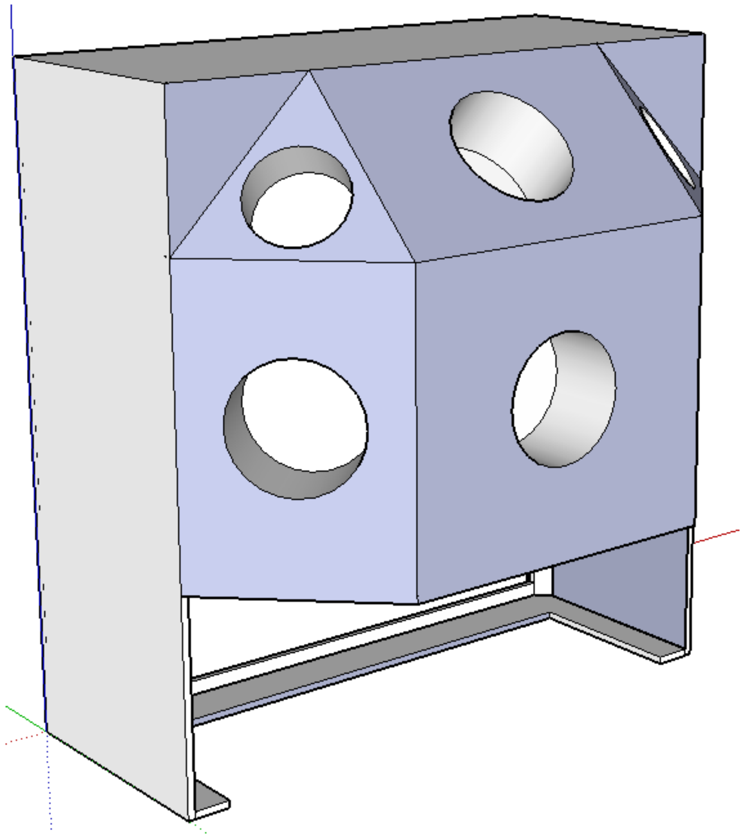

Figure 8.13. Preliminary casing design with use of *3D* model software

The casing has a special shape which makes it possible to embed the ultrasonic transceivers in a way that there are no protruding sensors and the sensors can be tightly placed in the casing. Therefore, even during some impact with a wall or putting some force by touching the sensors, the risk of damaging the sensors is minimized. Furthermore, the sensors are fixed and they do not change their position which makes it easier to interpret the signals. Another feature of this design is that it is possible to make the casing rainproof with the usage of waterproof sensors (like the ones in a car bumper) and silicon gap fillings.

The lower side of the casing was designed to protect the *IRRF*, but also to make it possible to adjust the beam angle. This is helpful for customizing the parameters accordingly to the user's height in order to minimize both the measurements and detection errors.

The inside of the casing holds the *PCBs*, connectors, wiring, some mechanical parts and battery.

Figure 8.14 presents the *3D* printer making a part of the designed custom case for the prototype.

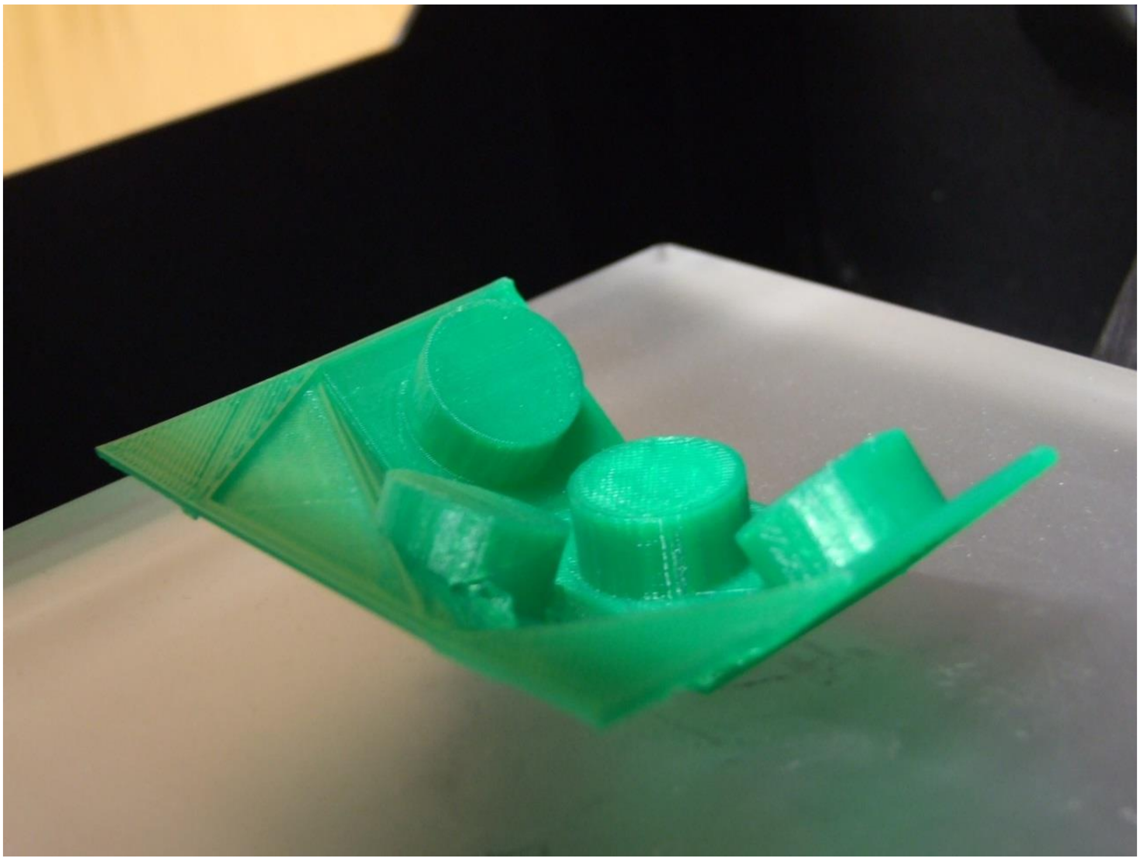

Figure 8.14. Part of the *3D* printed casing

3D printers are perfect for creating any kind of plastic cases for electronic devices. Despite that the unit cost is not so low, the overall costs are much lower if the design is in the preliminary stage and it is obvious that there will be major changes and tweaks. In that case creating the separate mold for every new design stage, even a simple one, would vastly elevate costs.

Additionally, a possibility of using different kinds and colors of plastic makes it possible to better evaluate the final look than by simply rendering the *3D* model of the design.

CHAPTER 9: CONCLUSIONS

In this dissertation, the development of the mobile safety system for the blind has been presented. Those kinds of aids are important not only from the engineering point of view but also from the humanitarian perspective.

The preliminary research conducted in the first stage of this dissertation resulted in the overview of the electronic aids for blind people. That information, combined with previous experiences with designing devices for blind people and also both cooperation and consultations with blind people and their teachers from the Special Educational Centre for Blind and Visually Impaired People made it possible to have developed and introduced the device that could help blind people to avoid dangerous objects and holes in the ground while blind users were walking.

The device subsystems were being designed to fulfill the goals regarding the usability, low energy consumption and also the price, since the major percentage of visually impaired people live in developing countries. In all stages of the design, special methods to minimize power consumption were used, including the energy debugging, which was crucial to reduce the development time.

To detect obstacles above the waist level, the 6-channel ultrasonic range finder was introduced. It is capable of detecting multiple objects at once and its range is over 4 m which is more than sufficient for blind people. The vulnerability to inclined planes was reduced with a special layout of the ultrasonic transducers that are fixed on the casing. With a simple digital interface, the multi-channel ultrasonic driver can also be used in other applications and it is scalable.

The next stage was the implementation of the path scanner subsystem, which is able to detect holes and road excavations. Preliminary tests had shown that non-stabilized infrared range finder feeds unreliable data and this data cannot be used in detecting small holes in the ground. Thus, some sort of stabilization algorithm had to be implemented. The addition of accelerometer and gyroscope to the system made possible to obtain the linear acceleration in the world format. The analysis of people's movement characteristics leaded to the development of the 2-stage *IRRF* stabilization algorithm based on zero velocity points (*ZVP*). This algorithm has proven to be effective and vastly increased the reliability of small holes and objects detection in the system. Additionally, the presented method can be scaled into the area scan system, just with implementing some transformation matrices. For this purpose the *2D IRRF* would have to be used. Given the fact that the device on the user's chest is usually situated approximately 1-1,5 m above the ground and the scan area should be around 2 m ahead, the scan angle of the *2D IRRF* could be only 12 degrees to meet the scanning space of 0,5 m width.

During the process of designing the interface for communication between the user and the device, a number of techniques were discussed with blind people, which would have potentially been used in the project. Since the device has to be used outside, most of the ideas which involved the hearing sense, did not quite appeal to the blind people, who often use the surrounding sounds to percept the environment and navigate safely. As a result of the mentioned consultations and preliminary tests, the 6-point vibrating bracelet was introduced to the project. This multi-tactile interface was quickly accepted by the users.

The system tests with blind people from the Special Educational Centre for Blind and Visually Impaired People were designed with guidance from teachers of this institution and also conducted under their direct supervision. Through dividing tests into stages where children were familiarized with the device and its functionality, they could touch and feel the device casing and shape before the proper test scenarios were conducted, the kids were focused, interested and pointed out some of their first thoughts which were very useful in tweaking the device to be more appropriate for blind users.

With the device and vibrating bracelet interface, after some learning period all the children were able to detect and avoid the hazardous obstacles, for instance, objects on the waist-up level, other people (stationary and in motion), etc. Also, they were able to react on detection of stairs (going up and down), holes of various heights and objects lying on the ground. The device was tested when the blind users were walking and also when they were staying still.

After the tests were done, the children were asked if they would use this kind of device on the everyday basis. They all answered yes, if only the device was affordable for them and slightly smaller. They also pointed out some interesting observations like: this device makes possible 'to feel the distance', with this device they are able to find open door in the wall, the vibrating bracelet could also be used as the interface in other devices for blind people; and finally that they would feel a little bit safer while walking with that device.

Thereby, the thesis that reads as follows:

It is possible to detect and inform about hazardous obstacles for blind people, in particular road holes and head level objects, using user-friendly electronic mobile system, when a blind person is walking;

has been proven.

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